TOP-DOWN MODULATION OF VISUAL ATTENTION

by

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Abstract

This body of work examines the effects of pre-cues on visual search for targets defined by a colour-orientation conjunction. Cueing the identity of targets enhanced the efficiency of search, with stronger effects from cueing the colour of the target compared to cueing its orientation, even though the targets were balanced for search efficiency within both orientation and colour dimensions. The colour advantage remained when the response to the target was task-irrelevant and occurred whether information was presented as visual cues or verbal cues. There was, however, evidence of automatic priming from the physical nature of cue stimuli playing a substantial role in guiding search, particular when based on the cue’s colour. Eye movement data from uncued trials indicated fixations were initially directed to a subset of items with the same colour. Cues were assumed to direct fixations within this colour-grouped array. Colour cueing effects reinforced the parsing of stimuli grouped by colour, while orientation cues enhanced local orientation disparities within the colour groups. The findings suggest that the advantage for colour cueing may be due to a combination of more efficient early segmentation of search items into colour groups and stronger grouping arising within these groups.

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CHAPTER 1

General Introduction

1.1: Introduction

The focus of this research is to examine how people look for an object in their visual field and how featural information about this object, such as its colour and orientation, affects this search behaviour. We undertake such search tasks all the time. Whether trying to find a train time at a station, a friend in a crowd or our socks in the washing basket, we are selecting visual information relevant to our specific goal and using this information to guide us to what we are looking for. That we do so in a vibrant and complex environment where many and varied items compete as potential targets, indicates that our visual system can select pertinent information efficiently. The efficiency of this selection process is related to the nature of the objects being searched through as well as user-controlled criteria. By measuring how this is reflected in search speed and eye fixations, this thesis addresses how prior knowledge about the search target affects the selection of information during visual search.

1.2: Response Measures

1.2.1: Reaction times

In the laboratory, researchers have typically investigated the processes underlying the visual selection of information by presenting a target stimulus amongst distractor items. Such a methodology allows for tight control of confounding factors present in more natural environments – such as in a lecture hall or train station. Participants are typically required to respond as to whether the target is present or absent, although for some studies the task has been to indicate a search-irrelevant feature possessed by the target (a compound task; cf. Olivers & Meeter, 2006). The speed of this response (reaction time or RT) and its accuracy are recorded. Several attention models have arisen from this experimental data (see 1.3), offering theoretical accounts of how visual information is processed.

1.2.2: Measuring eye movements

As well as search speed, the current set of studies includes data from detecting which stimuli are fixated during visual search (Chapters 5 and 6). Tracking eye movements has recently been used as a more immediate measure of the deployment of attention during search tasks (e.g., Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006; Rutishauser & Koch, 2007; Shen, Reingold, & Pomplun, 2000; Williams & Reingold, 2001). It allows the assessment of how the search develops; a factor not available from overall measures such as RTs or search accuracy. For example, pre-cueing the colour of a target may lead to shorter RTs. However, it would be unclear whether this prior knowledge is aiding the segmentation of the target from neighbouring distractors or directing fixations towards the group of stimuli with the same colour as the target. These processes could be better separated by examining whether eye movements were directed by the cue towards the target or cued distractors.

It is important to differentiate between overt deployment – reflected by eye movements – and covert deployment of attention. Overt deployment is achieved through rapid eye movements or saccades, between which the eyes are relatively stable, fixating an area of the visual environment. The rapid changes in eye position typically last around 40ms, occur around 3-4 per second (Becker 1991) and the eye is essentially blind during these movements (due to a process called saccadic suppression) while information is largely acquired during the relatively long fixations (approximately 250ms, Hoffman, 1998). The retina of the eye is not homogeneous with an area with the highest visual acuity – the fovea – positioned in the central two visual degrees. Saccades are used to orient the optical system so that the fovea receives information from the relevant areas of the visual field. These overt eye movements are complemented by a covert attentional system that offers heightened processing of specific areas of the visual field and are made via internal neural adjustment that can be initiated faster than overt mechanisms (e.g., Hoffman, 1975).

Evidence from studies of reading (e.g., Rayner, 1975) show that the destination of saccades is often guided by information from the periphery of the retina, suggesting that covert processes influence where the eyes are moved to next. It is generally accepted that this coupling is mandatory: covert attentional processes must be allocated to the saccade goal at some point prior to the saccade being made (e.g., Peterson, Kramer, & Irwin, 2004; see Klein, 1980, for opposing evidence). This link occurs whether the eye movement is under the control of the visual system's user, in response to an instruction, for example, or prompted by an external event, such as an unexpected onset or movement. In contrast, one can attend to items in the periphery without moving ones eyes (e.g., Posner, 1980; Yantis, 1998).

So can the tracking of eye movements be taken as an index of attentional deployment? It would seem that the positioning of eye movements and the deployment of attention are strongly related (e.g., Godijn & Theeuwes, 2003), with the destination of the saccade being foreshadowed by enhanced visual attentional processing. Their disassociation is only evident when saccades are voluntarily inhibited by the observer. I therefore consider the positions of eye fixations to index the deployment of both covert and overt attentional mechanisms, both processes will be considered when interpreting the eye movement data (Chapters 5 and 6).

1.3: Search Efficiency

This thesis focuses on the behaviour during search for a conjunction target, a ‘difficult’ task that takes longer as more search items are presented. The difficulty of a search, or its efficiency, is indexed by the relationship between how quickly the target is found with the number items being searched (e.g., the search slope of a RT-array size graph). It helps to outline extreme exemplars. Easy efficient search is believed to occur in parallel and occurs when RTs are unaffected by the number of distractors. The resultant search slope is therefore flat. For example, searching for a red item amongst green distractors, the number of green distractors does not affect the time taken to find the target (e.g., Nagy & Sanchez, 1990). This easy, ‘efficient’ search tends to occur when the target is defined by a single physical feature not shared by any other items in the display (e.g., colour, luminance, size or motion; see Figure 1.1a). In the studies outlined in Chapter 2, target discriminability was balanced within orientation and colour dimensions by assessing search speed and efficiency when targets only differed from distractors by colour or orientation. The RT slopes from these conditions were flat or near flat (see Figure 2.2) and therefore efficient.

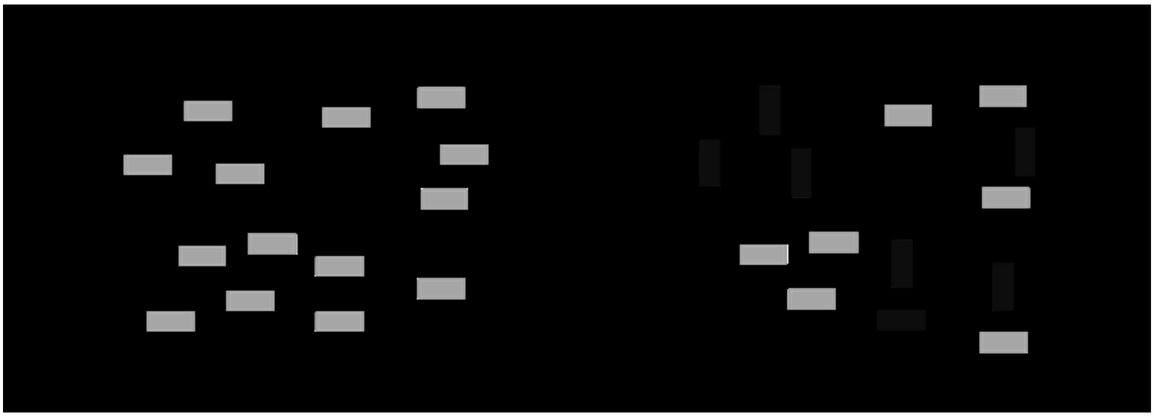

Figure 1.1: The speed of finding targets defined by a single feature (Fig. 1.1a) typically do not change with increasing size of display, while RTs for a conjunction search (Fig. 1.1b) increase the larger the array size.

The independence between the size of array and RTs for efficient search can be contrasted with RT functions that show a linear increase in RTs as the number of non-target items in the display increase. The processes involved in these difficult, 'inefficient' searches are usually assumed to be serial in nature. RT slopes on target-absent trials that are twice as steep as slopes from target-present trials is consistent with a random, serial self-terminating search (Sternberg, 1966), so that each item is assessed at a rate of one every 40-60ms. Therefore on target-present trials, attention is required, on average, to visit half the items before directed to the target. When the target is not present, a more exhaustive search is required. Therefore, increasing the number of search items affects performance on target-absent trials to a greater extent than target-present trials. Patterns consistent with serial search are typically found when targets are defined by a spatial conjunction (e.g., T amongst Ls) or a conjunction of features (e.g., a conjunction of luminance and orientation, see Figure 1.1b). Indeed, such a pattern is evident in the colour-orientation conjunction task used through-out the thesis (e.g., Figure 2.2).

1.4: Attentional Models

These experimental findings have, among other factors, led to the development of several theories of visual attention as researchers attempt to build coherent, interconnected models to how visual information is selected and processed.

1.4.1: Guided Search Theory (GST). One of the most influential model of visual attention is the GST developed by Cave and Wolfe (1990; Wolfe, Cave, & Franzel, 1989; Wolfe, Yu, Stewart, Shorter, Friedman-Hill, & Cave, 1990; Wolfe, 1994). GST is a two-stage model, with an initial stage that processes primitive features from visual items spatially in parallel. Featural information from search stimuli is processed separately within dimension-specific modules (e.g., colour, orientation, shape etc.). Each of these modules calculates activations within that particular dimension for a specific item location on a feature map. The activation is determined two-fold. Stimulus-driven, bottom-up factors are dependent on the feature differences between the item and adjacent items, while the top-down input is an index of task demands and knowledge about the different stimuli – such as whether the item's feature matches prior knowledge about the search target. The activations from these disparate maps are summed onto an overall saliency map. Focal attention is then guided to the location with the maximal activation. If the search target is not located there, the next 'highest' activation is chosen and so on until the search is concluded. This model proposes interactions between the first parallel and second more serial levels of processing. Therefore, rather than requiring attention to serially check all items for the target, it is guided to the most likely candidates. For example, when the target is a blue horizontal item amongst blue vertical and green horizontal distractors (as on half the trials in the current set of studies), following the parallel stage increased activations occur at the locations of blue and horizontal items. The highest peak would belong to the target and search would therefore be preferentially guided towards this location. If this ranking of items worked seamlessly, we would expect a conjunction target to produce a flat RT slope – e.g., with search speed unchanged by the array size. However, the model assumes the process of guiding attention to be noisy, with this noise allowing distractors to attain higher activations than that of the target. The more items in the search, therefore, the greater the likelihood of the focus of attention being misdirected towards these distractors, resulting in RTs increasing with item number (e.g., a positive RT slope).

1.4.2: Attentional Engagement Theory (AET). A somewhat different approach was taken by Duncan and Humphreys (1989) in their AET. They posit that search difficulty – indexed by RT slope – is dependent on the similarity between the target and distractors as well as the similarity between the distractors themselves. Difficulty increases as target and distractors become more similar, and search also gets more difficult as distractors get less similar (Duncan & Humphreys, 1989). For example, a feature-defined singleton search is more efficient compared to a conjunction search as target-distractor similarity is greater in the former compared to the latter as is the similarity between distractors.

As with GST, AET includes an initial parallel stage that segments the search items into structural units that share the same features. These units then compete for access to the visual short-term memory (VSTM) and access to awareness, before an action can be made. It should be noted that within this framework no clear distinction is made between serial and parallel search modes. Access to the VSTM is limited. In the parallel processing stage, different structural units are given selection weightings that increase or decrease a particular unit's speed and likelihood of it gaining admittance to VSTM. This process has a limited capacity, so that an increase in weighting to one group of items would alter the distribution of weightings to the other structural units. The selection system changes weights depending on two factors. First, how close the unit matches an internal template of the search target (e.g., its colour or shape) would increase the unit's weight. Non-targets with similar featural values to the target (and, on cued trials, matching cued information) would attract similar weight as the target item and would therefore offer strong competition in accessing VSTM. A second influence is the linking of the weights assigned to units, whereby any change in weight for one unit is distributed to other units in proportion to the strength of perceptual grouping between them. This is particularly effective in rejecting strongly grouped distractors – ‘spreading suppression’ – so that, for example, rejecting a stimulus of one colour would lead to distractors sharing that colour being suppressed. This allows targets in feature-singleton searches to gain access to the VSTM efficiently.

1.4.3: Dimensional Action Model (DA). This model (Cohen & Shoup, 1997, 2000; Cohen & Feintuch, 2002) is based upon the framework as GST. However, rather than a single response selection mechanism, DA proposed the existence of separate mechanisms linked to each dimensional module. Within this framework, the features of visual stimuli from different dimensions are first processed in the separate modules, with the location information retained during processing. The response assignments for each feature are then determined separately within each dimension. For example, the assignment of a left-handed response to a green stimulus and a right-handed response to a blue stimulus is made within the colour dimension. These multiple response assignments are linked to a central mechanism so that a single motor output can be executed. If there are competing response assignments within a dimension, then the activation passed on to the central mechanism is delayed (Cohen & Shoup, 1997). Any competition between response assignments is resolved by spatial attention. To activate the central response mechanism, the activations from the separate modules are required to reach a certain threshold. Spatial attention amplifies the activation of the relevant module (and its associated response) to a level above the threshold required for an overt response to be released. The model argues that the threshold cannot be attained – and a response made – without the input of spatial attention.

Cohen and Shoup (2000) extended this framework to include a conjunction map representing conjunctions of features from different dimensional modules. The nature of this representation is determined by which features are allowed access to the conjunction map at a particular time. This map can also be pre-configured prior to the presentation of visual stimuli, so only the relevant features (e.g., those possessed by the target) can gain access. The model, therefore, neatly explains efficient conjunction search, while search for more than one target would require more a serial processing of visual information.

1.5: Guidance during search

Although the above models disagree on the mechanisms, all suggest that search for a conjunction target by a combination of top-down factors, which are under the control of the visual system's user, and bottom-up effects driven by the physical properties of the search items. Many studies have investigated the effects driven by physical differences in search items (see Wolfe, 1998, for a review). As the current research largely focuses on the top-down effects of cueing in search, here is not the place to fully expound on these issues. However, as cueing effects may operate in parallel with bottom-up biases (e.g., Chapter 4), it is worthwhile outlining bottom-up factors occurring in this thesis.

1.5.1: Ratio effect. In several studies, the ratio between the two types of distractors present in conjunction search was manipulated. Search has been shown to be more efficient when the target falls within the smaller of two groups of distractors than when the ratio is balanced (Bacon & Egeth, 1997; Egeth, Vrizi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Sobel & Cave, 2002). This pattern of 'subset search' has been interpreted to reflect bottom-up processes directing search towards the smaller group of stimuli sharing a feature with the target, with little effect from top-down instruction to restrict search to a specific distractor type (Sobel & Cave, 2002). Eye movement data also indicate increased fixating of the items in the minority subset (e.g., Williams & Reingold, 2001). These findings sit well with both GST and AET models, which posit that salience is indexed to the similarities of local distractors, increasing with increases in differences between neighbouring stimuli. Search would therefore be guided to smaller groups of stimuli due to the greater local differences between adjacent items.

1.5.2: Spatial factors. Several researchers have also demonstrated that the spatial grouping of adjacent distractors is an important factor during conjunction search (e.g., Poisson & Wilkinson, 1992; Treisman, 1982). In their Experiment 2, Poisson and Wilkinson compared the effect of varying the distractor ratio in a colour-orientation conjunction search task (see 1.5.1) when the stimuli were spatially random compared with when a homogenous group of distractors surrounded the target. While search with randomised configurations showed a typical ratio effect (e.g., shorter RTs at extreme ratios), RTs in the grouped condition were largely independent of the ratio between distractor types. Poisson and Wilkinson took this as evidence of spatial groups being processed as simple units irrespective of the numbers of distractors present.

1.5.3: Target-specific guidance. While the innate nature of array items affects search efficiency, the degree to which they match the target template also influences search (see 1.4). In most visual search experiments, participants look for a specific type of stimulus – the target – over hundreds of trials. Information about the target (such as its colour and/or orientation) therefore biases search towards stimuli possessing these features (e.g., Findlay, 1997; Findlay et al., 2001; Hannus et al., 2006; Kim & Cave, 1995; Kim & Cave, 1999; Rutishauser & Koch, 2007; Shen et al., 2000; Williams & Reingold, 2001). For example, Kim and Cave (1995, 1999) used a probe dot methodology to measure the deployment of attention during a conjunction search. Probes were detected quicker when position at the location of distractors sharing a feature with the target compared to when they were displayed at the position of distractors with no relation to the target. This is addressed by the models of visual search by increased activation of the location of these stimuli (GST) or increased competitiveness of items matching this target-template (AET). Guidance from these top-down factors occurs either following experimental instructions or during practice trials if, for example, the task is to look for the odd-one-out.

1.5.4: Colour advantage. Little is included in the above attentional models above the relative inputs from different featural dimensions, despite strong evidence that top-down and bottom-up guidance varies depending on the featural information used to direct search.

1.5.4.1: Target-colour. A number studies have shown that search for a conjunction target defined by its colour can be highly efficient, and elements defined by their colour may be searched preferentially in relation to stimuli defined along other dimensions. Williams and Reingold (2001), for example, measured eye movements during different triple-conjunction search tasks while varying the discriminability of stimuli along one dimension. Search targets shared one feature with each type of distractor and were a conjunction of colour (red vs. blue), orientation (upright vs. rotated 90º clockwise) and shape, with discriminability in the shape dimension either high (C vs. T) or low (E vs. F). Target identity was consistent for each participant who had to decide whether it was present or absent. The findings revealed that fixations were more likely to land on distractors with the same colour as the target compared to those sharing either of the other two dimensions. This bias was more pronounced when the discriminability of the stimuli within one of the other dimensions (shape) was more difficult (E vs. F), with the shape dimension only guiding behaviour when participants were searching for a C vs. T. Similarly, in colour and orientation conjunction searches both Zohary and Hochstein (1988) and Poisson and Wilkinson (1992) found that search to be preferentially directed towards stimuli defined by colour compared to those defined by orientation. By manipulating distractor ratio, both studies found that search was biased towards stimuli with the target-colour where search strategy based upon the target's orientation would be better, although this preference was only evident in the target-absent data of Poisson and Wilkinson.

1.5.4.2: Pre-cueing. Preferential guidance has also been generated following colour information presented prior to a search. For example, Williams (1966) recorded the eye movements during a search task for an item with a particular two-digit number (e.g., 45), while distractors possessed the remainder of numbers from 0 to 99. All stimuli were also defined by a conjunction of size, colour or shape. He found that, even when prompted by the information about two features of the target (e.g., its colour *and* shape) fixations were preferentially directed towards stimuli matching target's colour, rather than its size or, in this example, its shape.

Recently, moreover, Hannus et al. (2006) used a pre-cueing stimulus to indicate which item in the following feature-defined or colour-orientation conjunction search participants should look for and fixate. The discriminability for both dimensions had been balanced so that in a feature-defined search there was no difference in the probability of a saccade directed to a stimulus with the cued colour or orientation. However, in the conjunction search there was a large decrease in the likelihood of the fixation directed to a stimulus with the cued orientation, while there was no change for the colour dimension between the two search types. Müller et al. (2003) also cued participants on a trial-by-trial basis, specifying whether the target in a forthcoming efficient search differed from distractors along a particular dimension (colour or orientation), or particular values along each dimension (red vs. horizontal). Valid information about the dimension defining the target facilitated search, relative to no information. Invalid cueing slowed search. In addition to this, though, cueing a particular colour value also further benefited performance, while, in contrast, there were only modest effects of cueing a particular orientation value. Müller et al. proposed that, within the colour dimension, attention could be set for a particular feature value as well as for the dimension itself, while a top-down expectancy in the orientation domain could only be set for the dimension.

1.5.4.3: Pre-cueing orientation. Cueing is not just effective for colour, however. Hodsoll and Humphreys (2005) provided evidence of participants being able to set top-down expectancies for targets whose orientations were from a different category from those of distractors. Search is more efficient when targets and distractors differ in category of orientation (e.g., when the target is steep and the distractors shallow), compared to when targets and distractors are categorically similar (e.g., both are shallow), even when the absolute orientation difference between targets and distractors is the same in the categorical and non-categorical search tasks (Wolfe, Stewart, Friedman-Hill, & O'Connell, 1992). Hodsoll and Humphreys showed a more substantial advantage for categorically-defined targets when the targets were expected, with the effect much reduced when participants searched in a pure bottom-up manner for the 'odd-one-out'. This suggests that expectations can be set for at least coarse categories of orientation.

1.5.4.4: Working memory. A stronger effect on search performance has also been shown when the colour information from a pre-stimulus is held in working memory compared to when the shape of the cue was memorised. Several researchers (see Downing, 2000; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys & Heinke, 2006) have demonstrated that search behaviour is affected when a memorised cue is presented prior to the search display, even when the cue is irrelevant to the search task. For example, Soto and colleagues (Soto et al., 2005) presented observers with an orientation-defined search, with each of the search items surrounded be search-irrelevant coloured stimuli. Search RTs were affected when the colour or shape of a cue presented before the search was held in memory matched that of a stimulus containing one of the search items. RTs were shorter when the feature value held in working memory matched the stimulus containing the target, while search was slower when value matched a distractor-containing stimulus. The effects occurred even when the memorised feature never matched that of a stimulus containing the search target. The effect was larger when the colour of the cue matched a display stimulus compared to when the cue shared its shape with a display stimulus. However, there was little effect of an initial cue when it was not held in working memory and merely attended by participants (Soto et al., 2005, 2006). That is, the effect was due to top-down biases affecting search via working memory rather than bottom-up priming from the initial appearance of a working memory cue.

1.5.4.5: Non-explicit effects. Initiatively, one might expect cueing effects to be due to processes explicitly linked to the cued information. However, non-predictive as well as predictive effects have been shown following both verbal cues – where the information prior to search is outlined as a word (e.g., ‘BLUE’; cf. Müller et al.,

2003) – and visual cues – where the predictive information is presented by the physical properties of the cueing stimulus, e.g., a blue patch (see Wolfe et al., 2004, for a comparison between cue types).

Several studies have shown ‘inadvertent’ effects on the deployment of attention from ‘word’ or verbal cues (Moores, Laiti, & Chelazzi, 2003; Huettig & Altman, 2005). In a visual search context, Moores et al. (2003) presented a verbal cue – such as the word ‘MOTORCYCLE’ – before briefly displaying a number of objects. When the target object was present, it matched the cued information. The other objects were either semantically related or unrelated to the cued information/target. While there was a higher probability of participants fixating the target following the cue, on target-absent trials a bias was also present towards items related semantically to the cue compared to control items. Moores et al. proposed that representations of objects semantically associated with the verbal cueing information are held in working memory and activated alongside that of the target following the presentation of the cue. Huettig and Altman (2005) demonstrated that ‘inadvertent’ guidance included objects in the same category as the cue. They displayed an array of objects at the same time as presenting as a sentence of language aurally. On hearing a word referring to a display object participants spontaneously fixated that item. However, eye movements were also directed to objects in the same category as the spoken word if the object matching the word was not present (e.g., on hearing the word ‘piano’, the probability of fixating the image of a trumpet increased). The authors concluded that eye movements were driven by similarities between the mental representations of the objects in the two modalities.

As outlined previously, search-irrelevant visual features of a cue held in working memory affect search behaviour (e.g., Soto et al., 2005). However, features of the cue stimulus not explicitly maintained in working memory also affect search. Using similar methodology as Soto et al. (2005), Soto and Humphreys (2009) found that when participants were required only to memorise the shape of a coloured cue, search was affected by the colour of the item (for contrasting results, see Olivers, Meijer, & Theeuwes, 2006). They proposed that the cue was coded in its entirety into working memory, so that both features (colour and shape) were memorised whether or not this was required.

Strong effects of the colour of the stimuli have also been evident with no overt demand that the cue stimuli be memorised. Consistent with previous studies (Goolsby & Suzuki, 2001; Huang, Holcombe, & Pashler, 2004; Kumada, 2001; Maljkovic & Nakayama, 1994; Meeter & Olivers, 2006; Müller, Krummenacher, & Heller, 2004; Theeuwes et al., 2006), Kristjánsson (2006) found shorter RTs in a feature-singleton search when the colour, orientation or spatial frequency of the target was the same in the present trial as in the previous trial, compared to when the target-feature changed. However, the effects of repeating the colour of the target were stronger and were also evident when colour was irrelevant to the search task. Analogous effects were apparent in a conjunction search task (McBride, Leonard, & Gilchrist, 2007).

While the above evidence reflects stronger attention guidance from the colour dimension, the role of top-down and bottom-up contributions have not been clearly separated however. For example, targets defined by colour differences relative to distractors may be found efficiently because there is rapid bottom-up organisation of elements into colour-based groups (see Braithwaite, Humphreys, & Hulleman, 2005), with colour differences between the groups serving to guide search to a target.

1.6: Outline of Thesis

The current body of work aims to explore the characteristics of top-down guidance from prior knowledge about the target. Initially (Chapter 2), I balance the targets and distractors to be used in the thesis for search efficiency within colour and orientation dimensions (e.g., Bacon & Egeth, 1997). In Chapter 3, I compare the effects of cueing the colour or orientation the target in a colour-orientation conjunction search, investigating at what level (e.g., response level, visual priming) these processes occur. Next, I investigate the time course of cueing, looking at effects from both predictive and non-predictive cue features (Chapter 4). In the final two chapters, the eye movements as well as RTs are measured in uncued (Chapter 5) and cued search (Chapter 6). This offers a more immediate measure of differences between colour and orientation cueing. As attentional models generally assume similar guidance across featural dimensions, any bias in our findings should be addressed by subsequent versions. I discuss these points in Chapter 7.

CHAPTER 2

Equating Search Efficiencies

For Stimuli Used In Chapters 3-6

2.0.1: Abstract

The majority of my thesis investigated the effects of cueing the colour or orientation of the target of an inefficient conjunction search task (see Chapter 3-6). However, in this series of studies I tested the target and distractor stimuli to be used in these cued tasks for differences in search efficiency within the colour and orientation dimensions. To avoid differential top-down cueing effects, participants performed an 'odd-one-out' task in which they searched for a feature singleton that could occur along either the colour or the orientation dimension. If the saliencies of the targets along each dimension were equated, then there should be no search advantage for colour- over orientation-defined targets. If saliencies were not equated, the stimuli were amended and retested. RT slopes from the accompanying conjunction search indicated whether it was inefficient. The resultant stimuli were then used in the cued conjunction tasks. Any differences between colour and orientation cueing effects, therefore, would not due to differences in search efficiency.

2.0.2: Introduction

This main focus of this thesis is to compare the effects of cueing the colour of a target of a colour-orientation conjunction search with the effects of cueing its orientation. Search is for a blue horizontal or green vertical target amongst blue vertical and green horizontal distractors. However, first it was essential to control any bottom-up differences in search efficiency between the two dimensions (see 1.5.4) prior to undertaking the cued experiments. To do so, following Bacon & Egeth (1997), targets and distractors were presented in searches defined by either colour or orientation, for example a blue horizontal surrounded by blue verticals versus when it was surrounded by green horizontals. In pilot studies, the saturation levels of the colours were reduced until search performances roughly matched. Using these colour levels, further studies were undertaken to determine whether search RTs differed significantly between colour and orientation-defined displays (see Experiments 2.1.1-2.1.2). Following these studies, several experiments (see Experiments 2.2-2.4) were required to check that search efficiency remained balanced with the minor changes to items required for the cued experiments of Chapters 3-6. With each stimulus set, a conjunction search was also undertaken to check the efficiency of the resulting search. It is important that the search was inefficient to allow for the possibility that top-down cueing may modulate slope as well as the intercept of the RT function (see 1.3). Therefore, it was imperative therefore to establish that search RTs increase with item number before the cueing methodology was introduced.

It is worthwhile considering, however, whether a search metric should be used to balance performance for another search task. The purpose of the studies in Chapter 2 was to match the discriminability of the target from distractors within two dimensions: colour and orientation. On one hand, in both tasks items are displays in a pseudo-random configuration. The impact on search performance of differences in discrimination between stimuli therefore varies, depending on the number and type of items that are adjacent to the target. As a second consideration, search involves several stages, for example, detection, discrimination, identification, response. Using a search task to balance both these processes and local discrimination factors would therefore seem a valid method to control for differences in similar processes that may occur in a conjunction search.

It may be, however, that the processes occurring in the efficient, feature-defined search using in this chapter are distinct to those occurring in the conjunction tasks used in Chapter 3-6 (e.g., Treisman & Gelade, 1980; Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006). A different approach would be to undertake a simple discrimination task using two coloured bars which either differed in colour or orientation. The stimuli could then be manipulated until the speed with which the items could be differentiated within each dimension matched. By equating the speed of this forced-choice between feature values within colour and orientation, the ease with which targets can be determined and balanced. While this would directly control for item-to-item discriminability, the task may be too simple in controlling for similar processes occurring in search (see above). Target-distractor discriminability for a conjunction search is determined by several local comparisons and therefore balancing between just two items may not be adequate. Following similar methodologies set out by Bacon and Egeth (1997) and Hannus et al. (2006), I would therefore contend that balancing the efficiency of targets in colour- and orientation-defined search tasks is a suitable method to match the discriminability within these two dimensions for stimuli in a conjunction search.

Therefore, the saturation levels of colours to be used in Chapters 3-6 were first reduced and the performance in colour- and orientation-defined search compared. This comparison was conducted five times (Experiments 2.1-2.4) in order to ensure that the stimuli used in the different subsequent experiments were also equated. Experiment 2.1.2 was based around the stimuli used in Experiments 3.1. Details of a preliminary study using stimuli with higher colour saturation levels were also included (Experiment 2.1.1) to determine the sensitivity of the RTs to adjustments to the search items. For Experiment 2.2, stimuli included irrelevant features (required for compound search in Experiment 3.3) while the dimensions of stimuli were increased in Experiment 2.3 (and consequently used in Experiments 3.4, 4.1-4.3). In Chapters 5-6, the items and item distribution had to be altered to allow for accurate eye-tracking.

The spatial layout and stimuli of Experiment 2.4 matched that for Experiments 5.1-2, 6.1-6.3.

Experiment 2.1.1: Stimuli for Experiments 3.1 and 3.2
Higher colour saturation levels

2.1.1.1: Introduction

Following initial exploratory pilot studies, the first full experiment was undertaken with colour levels shown in Table 2.1 (the colours had been desaturated in comparison to normal levels; Bacon & Egeth, 1997). Analysis of the feature-defined trials will indicate whether the salience of the targets of colour- and orientation-defined searches was equated.

2.1.1.2: Method

Participants. Ten University of Birmingham students, one male, nine female, aged between 18 and 30 (average age 20.9) took part in the experiment. All had self-reported normal or corrected-to-normal vision; and had normal colour perception assessed using *Ishihara's Tests for Colour-Blindness* (Ishihara, 1981). To pass the assessment, participants were required to successfully identify the figures on the first five slides of the test booklet. All participants were naïve as to the purpose of the experiment.

Apparatus. Stimuli were presented at 1024 × 768 pixel resolution on a 17″ colour Samsung SyncMaster 793s monitor, driven by an Intel Pentium 4 PC with a Radeon 9000 AGP Pro video card. The stimuli were generated by an E-Prime programme (Schneider, Eschman & Zuccolotto, 2002) at a screen resolution of 640 × 480 that recorded RTs and accuracy via a standard UK keyboard. Audio feedback was provided by stereo Cambridge Soundworks speakers. Participants sat approximately 0.6m from the screen in a well-lit room.

Stimuli. Prior to each trial, a white fixation cross was presented, 0.1cm thick (visual angle of 0.1^{o} at a viewing distance of 0.6m), 0.5cm wide (0.48^{o}) by 0.5cm tall (0.48^{o}). All the stimuli were presented on a black background and comprised either blue vertical, blue horizontal, green vertical or green horizontal bars. The dimensions of the bars were 0.65cm (visual angle of 0.62^{o}) long by 0.15cm (0.14^{o}) wide. Prior to the study, exploratory case studies were undertaken varying the saturation of the colour, until an approximate balance between RTs for colour- and orientation-defined search (these studies used the same methodology as the procedure described below). The colour levels shown the current study are shown in Table 2.1.

Design. For the feature-singleton task, there were three main independent variables: the defining dimension (colour, orientation), array size (7, 11, 15) and target presence (present, absent), while there were only two main independent variables for the conjunction search task (array size, target presence).

Procedure. Half the participants performed the feature-singleton task, followed by the conjunction task, while the order was reversed for the other participants. Participants were instructed to search for a stimulus that was the odd-one-out from the array. First, a fixation cross was present for 1000ms, then a 100ms inter-stimulus interval (ISI) before an array of stimuli with one target and either six or 10 or 14 distractors. The search stimuli were presented randomly within a rough, invisible circle of diameter 5.5cm (5.25^{o}) with 21 possible positions. The circle was positioned in the middle of the screen and stimuli positions were jittered (+/- 0.1^{o}) vertically and horizontal to lessen spatial interactions between distractors. The defining dimension and target for each array was varied trial-on-trial in equal numbers. For colour-defined search, targets and distractors possessed different colours yet the same orientation (blue horizontal target vs. green horizontal distractors, or green vertical target vs. blue vertical distractors). For orientation-defined search, the target-distractor relationship differed only along the orientation dimension (blue horizontal target vs. blue vertical distractors; or green vertical target vs. green horizontal distractors). As the search dimension was defined by the target, the displays for target-absent trials did not differ in defining dimension. When the target was absent (50% of the time), it was replaced by a distractor. See Figure 2.1 for examples.

Participants undertook 12 practice trials followed by three blocks of 144 experimental trials. They were asked to indicate whether the search target was present or absent by pressing either ‘Z’ or ‘M’ on the computer keyboard (the key assignment was reversed for half the participants). Feedback was provided. If the response was correct, participants heard a medium pitched sound and the word ‘Correct’ was displayed. If incorrect, a lower note was played and the word ‘Incorrect’ was displayed instead. The time until participants’ response was recorded (RTs), with the accuracy of the response also noted.

The methodology for the conjunction task matched that of the feature-defined task except for the following. While the targets could be either a green vertical or blue horizontal bar (25% of the time, each) or absent (50% of the time), half the distractors were blue vertical bars and the other half were green horizontal bars. When the target was absent, a randomly chosen distractor replaced the target. Due to high error rates during piloting, participants were informed about the nature of the targets prior to the experiment, with graphical representations of the target images presented adjacent to the monitor during the task. There were 18 practice trials followed by a single block of 144.

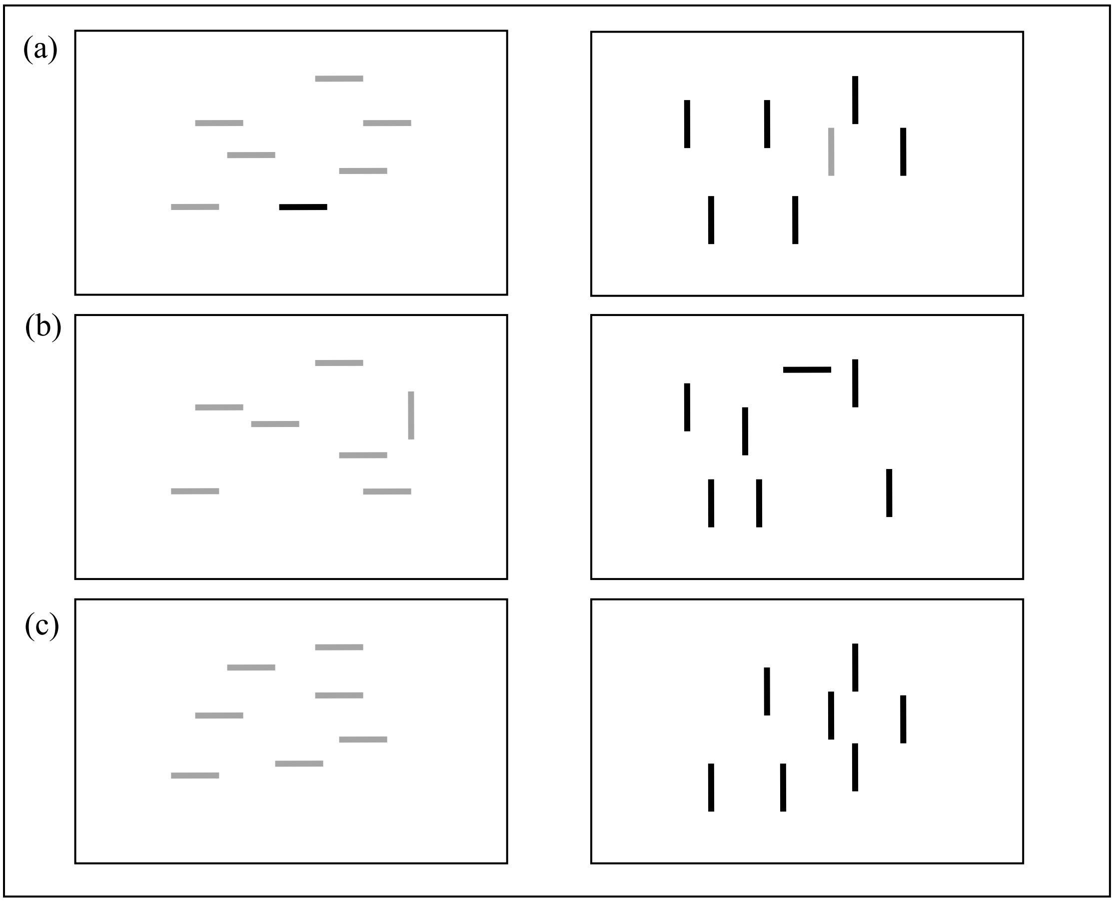

Figure 2.1. Examples of seven-item arrays displays used for the feature-defined search task in Experiments 2.1-2.7 (11- and 15-item displays were also presented). Blue items are shown as black, green as grey and the black background as white (see Table 2.1 for details of the colours). Fig. 2.1a shows a colour-defined search, Fig. 2.1b an orientation-defined search, Fig. 2.1c a target-absent search.

2.1.1.3: Results

In the conjunction task, some participants required breaks in the middle of the block of trials. For those analyses, these trials were discarded (RTs>5000ms). Less than 1% of data were removed as a consequence. All ANOVAs report the partial eta-squared (partial η^2) statistic which describes the proportion of total variability attributable to the particular factor (see Olejnik & Algina, 2003). To control the family-wise error rate, the alpha level was adjusted when multiple ANOVAs were undertaken on the same data and Huynh-Feldt adjustments were used on probabilities where necessary. All *post hoc* pair-wise comparisons included Bonferroni adjustments and were measured as significant at the $p<0.05$ level.

RTs. For the feature-singleton task, the data were pooled across trials within the target-defining dimension (colour or orientation) and median RTs for each participant were calculated. As target-absent displays were the same for colour- and orientation-defined trials, they were treated as catch trials and only target-present data were analysed. Group means from target-present trials are presented in Figure 2.2 (alongside data from Experiment 2.1.2). A two-factor ANOVA (defining dimension, array size) was used to analyse the feature-singleton data. This showed a significant effect of defining dimension ($F(1,9)=17.4$, $p=0.002$, partial $\eta^2=0.659$). RTs colour-defined targets were shorter than those to orientation-defined displays (561ms versus 610ms). No other effects or interactions reached significance (all ps>0.1).

Data from the conjunction task were pooled across target type and were analysed using a two-factor ANOVA (array size, target presence). Means are shown in Figure 2.2 (alongside data from Experiment 2.1.2). The data were typical of an inefficient search task (Wolfe, 1998). There were significant main effects of array size ($F(2,18)=25.6$, $p<0.001$, partial $\eta^2=0.74$) and target presence ($F(1,9)=58.1$, $p<0.001$, partial $\eta^2=0.866$) and a significant interaction between target presence and array size ($F(2,18)=3.7$, $p=0.045$, partial $\eta^2=0.291$). The interaction was indicative of a steeper search slope for target-absent trials (60ms/item) compared to target-present trials (20ms/item).

Accuracy. In both search tasks performance was accurate and there was no speed-accuracy trade-off. Errors are presented in Table 2.2.

2.1.1.4: Discussion

RTs were shorter on colour-defined trials relative to orientation-defined displays. This indicates that the salience of the targets within the two dimensions were not equated, although the resultant conjunction search was inefficient.

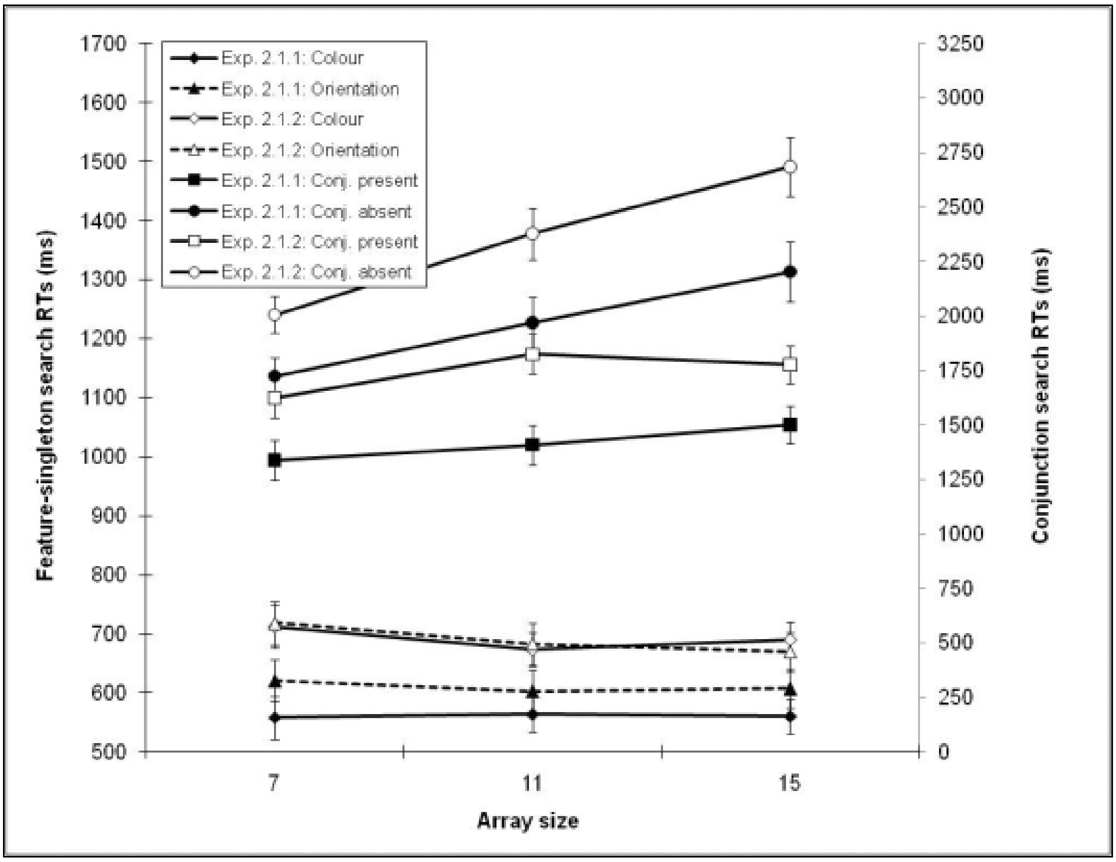

Figure 2.2. Mean RTs (+/- one standard error) from the feature-singleton and conjunction search tasks in Experiments 2.1.1 and 2.1.2. While only target-present data from the feature-singleton task are shown, both present and absent data from conjunction search trials are included. All data are separated by array size, however the feature-singleton data are split by defining dimension (colour or orientation).

Experiment 2.1.2: Stimuli for Experiments 3.1 and 3.2
Lower colour saturation levels

2.1.2.1: Introduction

The previous experiment demonstrated an advantage for colour-defined targets. Here, the colour saturation levels of the stimuli were reduced (see Table 2.1 for details) and the methodology of Experiment 2.1.1 repeated with the new stimuli. Differences to the previous experiment are outlined below.

Experiment	**Colour**	**Hue**	**Saturation**	**Luminance**	**Photometer reading (cdm^{-2})**
2.1.1	Blue	140	80	120	-
2.1.1	Green	80	80	120	-
2.1.2-2.3	Blue	140	40	120	25.79
2.1.2-2.3	Green	80	40	120	28.28
2.2-2.3	Grey	160	0	200	69.95
2.1.1-2.3	White	160	0	240	121.7
2.1.1-2.3	Black	160	0	0	4.31
2.4	Blue	140	40	120	12.16
2.4	Green	80	40	120	12.16
2.4	Grey	160	0	200	34.26
2.4	White	160	0	240	143.13
2.4	Black	160	0	0	6.02

Table 2.1. Colour levels used for the stimuli all experiments. Hue, saturation and luminance levels were adjusted using the Paint computer programme. Independent photometer readings, when taken, were from the Salford Electrical Instruments Exposure Photometer.

2.1.2.2: Method

Participants. Ten University of Birmingham students, one male, nine female, aged between 18 and 56 (average age 24.9) took part in the experiment.

Stimuli. The saturations of the colours used for the search items were reduced. Stimulus luminance was also independently measured using a Salford Electrical Instruments Exposure Photometer (see Table 2.1 for details).

2.1.2.3: Results

RTs. Data were cleaned as in Experiment 2.1.1. As previously, for the feature singleton task, the data were pooled across trials within the target-defining dimension (colour or orientation) and median RTs from target-present trials for each participant were calculated (target-absent trials were treated as catch trials). See Figure 2.2 for group means (together with those of Experiment 2.1.1). A two-factor ANOVA (task dimension, array size) showed a significant effect of array size ($F(2,18)=5.5$, $p=0.013$, partial $\eta^2=0.38$), with RTs decreasing with increasing array size. There was no difference between the RTs for colour- and orientation-defined targets ($F<1$), and no interaction with array size ($F<1$).

Data from the conjunction task were pooled across target type and were analysed using a two-factor ANOVA (array size, target presence). Means of both target-present and target-absent trials are shown in Figure 2.2. Again, the data typified the pattern expected from an inefficient search task (Wolfe, 1998). There were significant main effects of array size ($F(2,18)=26$, $p<0.001$, partial $\eta^2=0.742$) and target presence ($F(1,9)=84.1$, $p<0.001$, partial $\eta^2=0.903$) and a significant interaction between target presence and array size ($F(2,18)=9.2$, $p=0.002$, partial $\eta^2=0.505$).

Target-present trials showed a search slope of 19ms/item while the slope for target-absent trials was 85ms/item.

Accuracy. In both search tasks performance was accurate and there was no speed-accuracy trade-off. Errors are presented in Table 2.2.

Comparing RTs across experiments. To check the sensitivity of varying colour saturation, I compared RTs from target-present, feature-defined trials from Experiments 2.1.1 (high saturation) with the corresponding trials from Experiment 2.1.2 (low saturation). For parsimony, only effects or interactions across experiment number are reported. A mixed-design three-factor ANOVA (experiment, task dimension, array size) indicated a main effect of experiment ($F(1,18)=4.7$, $p=0.042$, partial $\eta^2=0.21$) and a task dimension x experiment number interaction, $F(1,18)=8.3$, $p=0.01$, partial $\eta^2=0.315$). RTs for a colour-defined target were significantly reduced as the level of colour saturation was also reduced (Experiment 2.1.1 versus Experiment 2.1.2; a difference of 131ms, $p=0.013$), while there was no corresponding difference when the target was defined by orientation (a difference of 79ms, $p=0.132$). No interactions reached significance ($ps>0.05$).

2.1.2.4: Discussion

The data confirm that (i) the orientation-defined targets used in Experiment 2.1.2 were as salient as the colour-defined targets (there were no differences in the slopes of the search functions), (ii) search for conjunction targets was relatively inefficient – demonstrating inefficient search is important in order to allow for the possibility that top-down cueing could alter the slope of the search function and (iii) search had not reach floor performance with the current stimuli (as demonstrated by an increase in RTs across Experiments 2.1.1-2.1.2). Given these patterns of performance, stimuli with the same feature values were used in Experiments 3.1 and 3.2.

Experiment 2.2: Stimuli for Experiment 3.3

2.2.1: Introduction

For Experiment 3.3, the response in the visual search task was changed from one based on the presence or absence of the target to a compound task (see Olivers & Meeters, 2006), where the response was determined by a search-irrelevant feature. This change to the physical make-up of the stimuli meant possible changes to the saliency of the targets along either the colour or orientation dimensions. To ensure that the stimuli were matched for this experiment, I replicated the odd-one-out and conjunction search tasks of Experiment 2.1.2 as well as using a compound task procedure for the conjunction task.

2.2.2: Method

As Experiment 2.1.2, except where outlined below.

Participants. Ten University of Birmingham students, three male, seven female, aged between 19 and 25 (average age 21.6) took part.

Stimuli. The search stimuli were similar to that of Experiment 2.1.2, except that small light grey symbols were added to the centre of all the items. These were either an ‘x’ or a ‘+’ and were distributed in a pseudo-random manner across distractors and targets, so that each feature was added to approximately half the stimuli. The choice of symbols was planned to minimise interaction with the orientation of the stimuli. Both features were three-pixels wide, leading to dimensions of 1mm (0.05°) by 1mm (0.05°), thickness 0.3mm (0.01°). Colour levels are outlined in Table 2.1. These symbols were also present on target stimuli, however they only indicated which response to make on conjunction displays (e.g., a compound search).

Procedure. As Experiment 2.1.2, except for the following. The response to the conjunction task was indicated by the symbol present on the target, with the nature of the response varied to control for handedness. To ensure that this change did not affect the efficiency of search, the number of trials for the conjunction task was increased, with 36 practice trials, followed by two blocks of 96. There were also only two blocks of 144 trials in the feature-singleton task.

2.2.3: Results

RTs. Cleaning and data analysis followed the procedure for Experiment 2.1.2, although the conjunction task did not generate target-absent data. Group means are shown in Figure 2.3.

The analysis of the feature-singleton task revealed a main effect of task dimension ($F(1,9)=6.7$, $p=0.029$, partial $\eta^2=0.428$), with orientation-defined targets detected significantly faster than colour-defined targets (685ms vs. 740ms). There was no main effect of array size ($F(2,18)=2.5$, $p=0.113$, partial $\eta^2=0.215$) or interaction with array size ($F<1$).

A one-factor ANOVA assessed the effects of the array size on the conjunction data. The main effect of array size was reliable ($F(2,18)=17.7$, $p<0.001$, partial $\eta^2=0.663$), and the overall slope of the search function was 33ms/item.

Accuracy. In both search tasks performance was accurate and there was no speed-accuracy trade-off. Errors are presented in Table 2.2.

<table>
<tr><th colspan="2">Experiment</th><th colspan="4">2.1.1</th><th colspan="4">2.1.2</th></tr>
<tr><th colspan="2">Array size</th><th>7</th><th colspan="2">11</th><th>15</th><th colspan="2">7</th><th>11</th><th>15</th></tr>
<tr><td colspan="2">Colour-defined search</td><td>98</td><td colspan="2">99</td><td>99</td><td colspan="2">97</td><td>96</td><td>98</td></tr>
<tr><td colspan="2">Orientation-defined search</td><td>97</td><td colspan="2">98</td><td>98</td><td colspan="2">97</td><td>98</td><td>97</td></tr>
<tr><td colspan="2">Conjunction search, target present</td><td>96</td><td colspan="2">95</td><td>92</td><td colspan="2">92</td><td>92</td><td>89</td></tr>
<tr><td colspan="2">Conjunction search, target absent</td><td>96</td><td colspan="2">98</td><td>96</td><td colspan="2">95</td><td>96</td><td>96</td></tr>
<tr><th colspan="2">Experiment</th><th colspan="4">2.2</th><th colspan="4">2.3</th></tr>
<tr><th colspan="2">Array size</th><th>7</th><th colspan="2">7</th><th>7</th><th colspan="2">7</th><th>11</th><th>15</th></tr>
<tr><td colspan="2">Colour-defined search</td><td>95</td><td colspan="2">96</td><td>96</td><td colspan="2">96</td><td>95</td><td>93</td></tr>
<tr><td colspan="2">Orientation-defined search</td><td>93</td><td colspan="2">96</td><td>96</td><td colspan="2">96</td><td>95</td><td>97</td></tr>
<tr><td colspan="2">Conjunction search, target present</td><td>95</td><td colspan="2">96</td><td>96</td><td colspan="2">96</td><td>94</td><td>95</td></tr>
<tr><th colspan="2">Experiment</th><th colspan="4">2.4</th><td colspan="4" rowspan="5"></td></tr>
<tr><th colspan="2">Array size</th><th colspan="3">5</th><th>9</th></tr>
<tr><td colspan="2">Colour-defined search</td><td colspan="3">-</td><td>95</td></tr>
<tr><td colspan="2">Orientation-defined search</td><td colspan="3">-</td><td>95</td></tr>
<tr><td colspan="2">Conjunction search, target present</td><td colspan="3">91</td><td>93</td></tr>
<tr><th>Experiment</th><th colspan="2">3.1</th><th colspan="3">3.2</th><th colspan="2">3.3</th><th colspan="2">3.4</th></tr>
<tr><th>Cue type</th><th colspan="2">Visual</th><th colspan="3">Visual</th><th colspan="2">Visual</th><th>Visual</th><th>Verbal</th></tr>
<tr><th>Array size</th><th>7</th><th>15</th><th>15</th><th>15</th><th>15</th><th>7</th><th>15</th><th>15</th><th>15</th></tr>
<tr><th>Distractor ratio (BVs: GHs)</th><th>4:4</th><th>7:7</th><th>3:11</th><th>7:7</th><th>11:3</th><th>4:4</th><th>7:7</th><th>7:7</th><th>7:7</th></tr>
<tr><td>Neutral</td><td>94</td><td>93</td><td>93</td><td>94</td><td>98</td><td>95</td><td>97</td><td>96</td><td>97</td></tr>
<tr><td>Valid colour cue</td><td>95</td><td>94</td><td>96</td><td>96</td><td>98</td><td>96</td><td>96</td><td>97</td><td>95</td></tr>
<tr><td>Invalid colour cue</td><td>88</td><td>85</td><td>91</td><td>84</td><td>82</td><td>91</td><td>93</td><td>96</td><td>96</td></tr>
<tr><td>Valid orientation cue</td><td>97</td><td>94</td><td>98</td><td>95</td><td>95</td><td>96</td><td>97</td><td>97</td><td>96</td></tr>
<tr><td>Invalid orientation cue</td><td>90</td><td>87</td><td>89</td><td>89</td><td>91</td><td>88</td><td>89</td><td>97</td><td>97</td></tr>
</table>

Table 2.2. The mean percentage accuracy across experiments in Chapters 2 and 3. When the distractor ratio is varied, BVs and GHs indicate the number of blue vertical and green horizontal distractors, respectively.

2.2.4: Discussion

The data show that (i) while RTs were quicker for orientation-defined targets, there were no differences in the slopes of the search functions, and (ii) the conjunction search task was relatively inefficient. The similar search slopes for colour and orientation-defined targets indicate that colour- and orientation-defined targets were equally efficient in attracting attention. In contrast to the other studies, in Experiment 2.3 search was faster for the target stimuli in the orientation dimension. This may have been because the search-irrelevant symbols added to the items increased the similarity of mean colour values across target and distractor items, while there was no effect on the similarity within the orientation dimension. Minimising the effect of these symbols on item colour was hindered by the necessity for them to be easily detectable. Although there was an advantage for orientation-defined targets, it should be noted that this would go against any tendency for colour search to be more efficient under conditions of top-down cueing (see 1.5.4).

Experiment 2.3: Stimuli for Experiments 3.4, 4.1-4.3

2.3.1: Introduction

In Experiments 3.4 and 4.1-4.3, I use larger stimuli from the ones employed in Experiments 3.1-3.3 to allow easier recognition of the search-irrelevant symbols indicating the required response to the target. To ensure that saliency was again matched across the dimensions I replicated the ‘odd-one-out’ and conjunction search tasks with these stimuli, in Experiment 2.3.

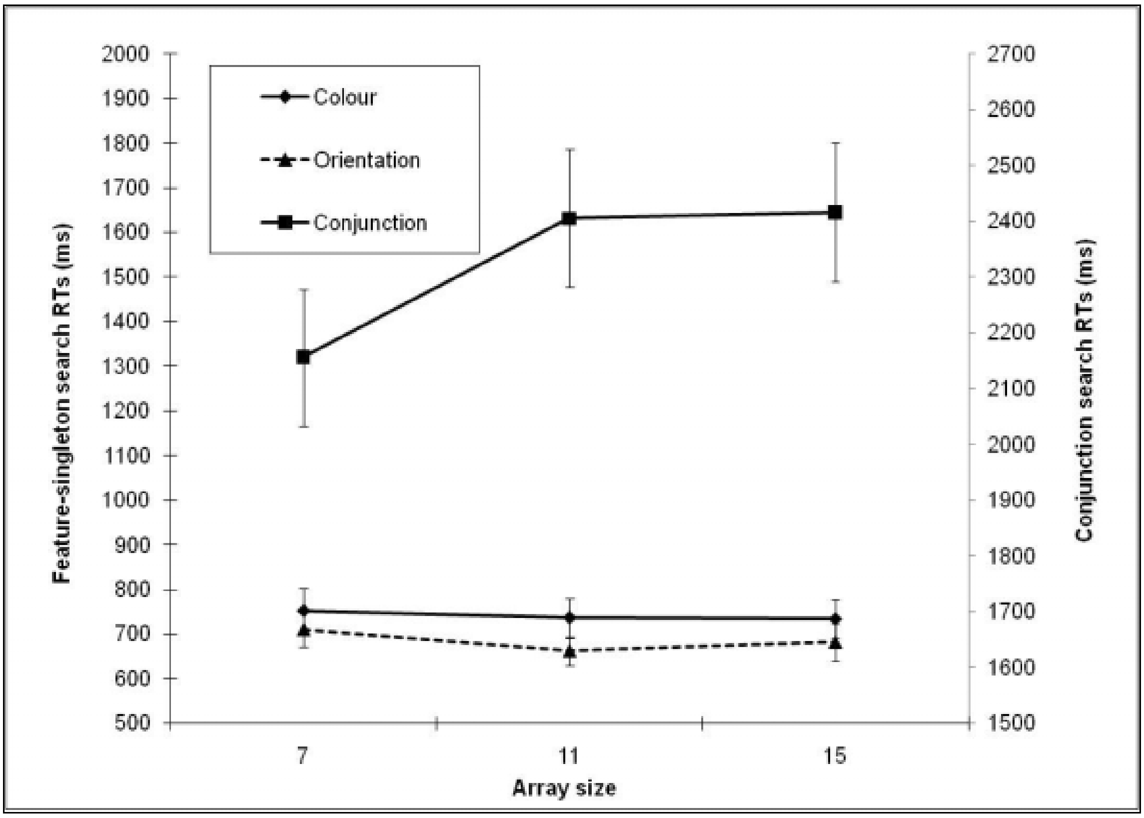

Figure 2.3 Mean RTs (+/- one standard error) from feature-singleton and conjunction trials in Experiment 2.2. Only target-present data are shown. All data are split by array size while the feature-singleton data are separated by defining dimension (colour or orientation).

2.3.2: Method

As Experiment 2.2, except for that outlined below.

Participants. Nine University of Birmingham students, two male, seven female, aged between 18 and 41 (average age of 24.3) took part.

Stimuli. The make-up of the stimuli was exactly the same as for Experiment 2.2, except the length and breadth of the bars and features were increased. The bars were therefore 0.8cm (0.77º) long by 0.2cm (0.19º) wide; symbols 0.2cm (0.19º) by 0.2cm (0.19º) and 0.025cm wide (0.024º). Further to this, the fixation cross was swapped for a fixation circle, 0.6cm diameter (visual angle of 0.57º).

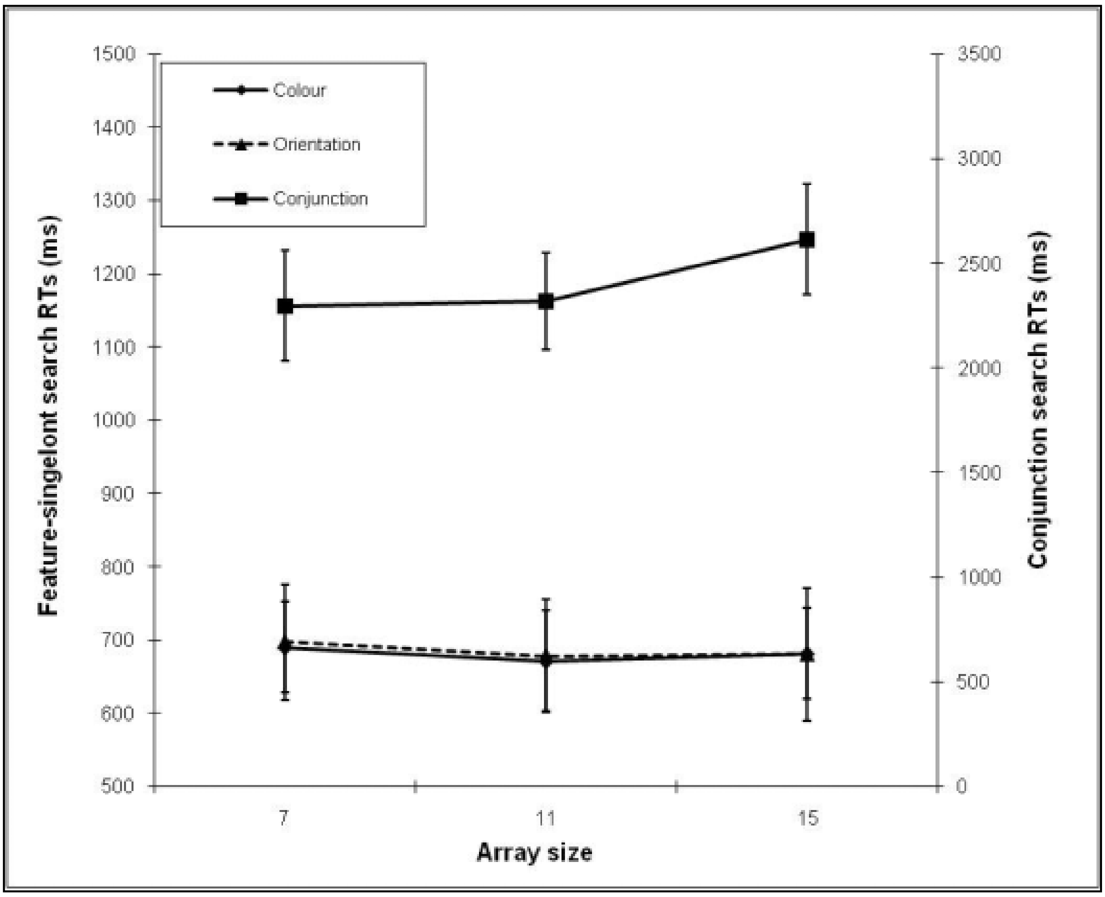

Figure 2.4. Mean RTs (+/- one standard error) from feature and conjunction search tasks (on separate axes) in Experiments 2.3. The data from the feature-defined task are separated by defining feature (colour or orientation) and array size (7, 11, 15), while the conjunction search data are separated only by array size.

2.3.3: Results

RTs. Cleaning and data analysis procedures were the same as in Experiments 2.2. Mean RTs across participants are shown in Figure 2.4. The analysis of the feature-singleton data showed no significant effects, with no difference between colour- and orientation-defined search (F<1) and no interaction with array size (F<1). Analysis of the conjunction data showed a significant effect of array size ($F(2,16)=7.4$, $p=0.011$, partial $\eta^2=0.480$), with an RT slope of 40ms/item

Accuracy. In both search tasks performance was accurate and there was no speed-accuracy trade-off. Errors are presented in Table 2.2.

2.3.4: Discussion

The data show that the small changes made to the items here eliminated any small advantage in overall RTs for orientation-defined targets. Moreover, there were again no differences in the search slopes for colour- and orientation-defined targets. As in the other control studies, conjunction search proved relatively inefficient. Stimuli with these values were therefore used in Experiments 3.4, 4.1-4.3.

Experiment 2.4: Stimuli for Experiments 5.1-5.2, 6.1-6.3

2.4.1: Introduction

The display density and presentation set-up had to be changed to allow accurate eye-tracking in Chapters 5-6. Fewer items (nine versus 15) were presented within the same search area, and the display monitor differed in resolution and size. These alterations dictated that further piloting of stimuli was required to control for bottom-up dimensional differences in search efficiency (see Bacon & Egeth, 1997). The stimuli were then used in Experiments 5.1 and 5.2 as well as in all experiments in Chapter 6.

2.4.2: Method

Unless otherwise mentioned the Method matched that of Experiment 2.3.

Participants. Ten University of Birmingham students, four male, six female, aged between 23 and 28 (average age 25.4) took part.

Apparatus. The stimuli were presented on a display PC with a 22-inch colour CRT monitor (ViewSonic P225f, 2004) at 1024 × 748 pixel resolution and a refresh rate of 100Hz. Audio feedback was provided by stereo Genius speakers. Participants used a chin rest 0.6m from the screen, in a dimly lit room with windows blacked-out to avoid luminance changes. The chin rest and monitor heights were adjusted for each participant so eye gaze was central to the display screen.

Stimuli. The colour levels are shown in Table 2.1. All the stimuli were presented on a grey background to facilitate eye tracking. The fixation circle was 0.6cm diameter (0.57º). The dimensions of the bars were 1cm (1º) long by 0.3cm (0.3º) wide. Grey symbols, '+'s or 'x's, were equally distributed across all stimuli. Colour levels are shown in Table 2.1.

Procedure. Trials matched those of Experiment 2.3 except for the following. Although visual reminders were presented adjacent to the computer monitor this only occurred during practice trials. Search displays involved nine bars (feature-defined tasks) or five or nine bars (the conjunction task) which were presented randomly within a central invisible circle of diameter 10cm (9.5°) with 12 possible positions, staggered to lessen spatial interactions between distractor stimuli. For the feature-singleton task, participants undertook 24 practice trials followed by two blocks of 80 experimental trials. On conjunction trials, there were 18 practice trials followed by two blocks of 48.

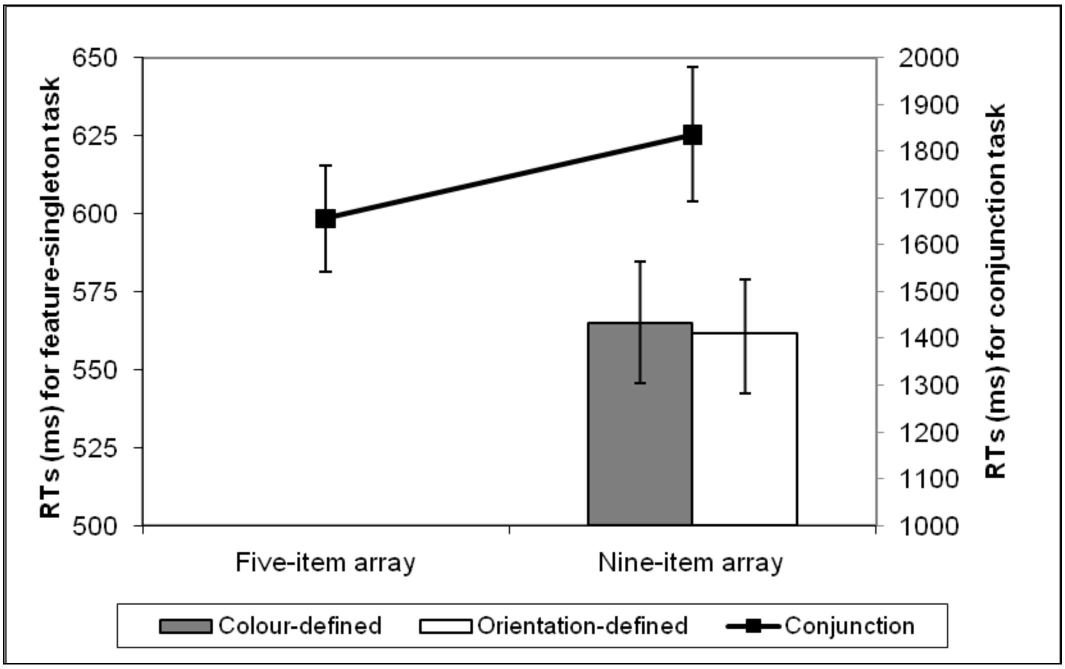

Figure 2.5. Means (+/- one standard error) of median RTs from Experiment 2.4, separated by search type (colour-, orientation- or conjunction-defined task) and array size (note only the conjunction-defined task included a five-item array). As previously, only target-present data are presented.

2.4.3: Results

RTs. Data were cleaned as in Experiment 2.3. The means of median RTs for both feature-singleton and conjunction search are shown in Figure 2.5.

A one-factor ANOVA showed no difference between RTs from colour- and orientation-defined displays (F<1). Data from the conjunction task were pooled across target type and were also analysed using a one-factor ANOVA (array size). The data were typical of an inefficient search task (Wolfe, 1998), with a borderline significant main effect of array size (F(1,9)=4.6, p=0.06, partial η^2=0.339) indicating an increase in RTs as array size increased. The search slope was 45ms/item.

Accuracy. In both search tasks, performance followed that of the RT data indicating there was no speed-accuracy trade-off. Errors are presented in Table 2.2.

2.4.4: Discussion

The data confirm that (i) the orientation-defined targets used here were as salient as the colour-defined targets, and (ii) search for conjunction targets was relatively inefficient. Given these patterns of search, the same feature values were used in Experiments 5.1 and 5.2. These in turn were used as the baseline condition for the cueing effects examined in Chapter 6.

2.5: General Discussion

The above findings demonstrate that in manipulating the colour of the target and distractor stimuli to be used in Chapters 3-6, I have controlled for differences in efficiency within colour and orientation dimensions (with the exception of Experiment 2.2). I also presented evidence that performance had not reached floor (see Experiment 2.1.1), indicating that the feature-defined search tasks undertaken to test efficiency were sensitive to the alterations of the stimuli. Conjunction search with the amended stimuli were also inefficient, with performance slowing with increased display size.

2.5.1: Null effect

However, there are statistical issues when depending on a null effect in measured values – e.g., no difference between search RTs. According to Howell (1992), a lack of an effect does not indicate that the means for a population of scores from one condition is the same as the mean of a population from another condition. Despite this, following an approach by Neyman and Pearson (1933), although we may not take the lack of an effect as proven, we can act as if it true until we collect data to suggest otherwise.

The question is, therefore, whether I have obtained enough data to act as if the data from colour- and orientation-defined searches were from the same population. It may be that a Type II error has been made (e.g., not finding a difference between populations that is there) and that the experiments (for example Experiment 2.1.2) lack the power to indicate whether RTs from two search conditions do or do not differ. Experiments with more power have better chances in correctly indentifying a false null hypothesis (e.g., that it is wrong that RTs from the two groups are from the same population). Therefore, if the power of experiments was high enough and there was still no difference between the two datasets, then we can more confidently indicate that the two RT samples come from the same population.

Acting retrospectively, I investigated the number of participants needed to be tested to offer the requisite level of power. To do this, an estimate of the effect size was necessary, which can be calculated by dividing the ‘critical difference’ between the two mean RTs by the standard deviation. Prior to this thesis, experiments were undertaken that looked at cueing the colour or orientation of conjunction targets that were not balanced for search efficiency (unpublished data from my Masters of Research work). Search was facilitated following colour cues vs. orientation cues by 102ms. The studies outlined in Chapter 2 here were undertaken to eliminate any contribution towards this colour advantage from stimulus-driven factors (e.g., Poisson & Wilkinson, 1992). Using the 104ms as the critical difference, this was divided the standard deviation of the Masters data (148ms), giving an effect size of 0.68. G*Power 3 software (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that for this effects size an experiment should have 15 participants to have the necessary power to accept the null hypothesis.

Across this chapter, nine or 10 participants were tested per experiment. It may be that this number was not sufficient to conclude that RTs were not different from colour- and orientation search. It must be noted that significant differences between search RTs were found from datasets from only 10 participants in both Experiment 2.1.1 and Experiment 2.2 with large effect sizes (partial η^2s of 0.659 and 0.428, respectively) indicating the differences were meaningful. Although the power of the experiments was not sufficient, this offers some evidence that enough participants were tested for a reasonable level of task sensitivity as to whether performances were matched with this sample size.

2.5.2: Conclusion

Despite issues with the number of participants tested per experiment (see above), the stimuli with the colour values were used in the neutral and cued displays outlined in the rest of the thesis.

CHAPTER 3

Featural Guidance in Conjunction Search: The Contrast Between Orientation and Colour

Chapter 3 is a short version of Anderson, G., M., Heinke., D., and Humphreys, G., W. (2010). Featural guidance in conjunction search: The contrast between orientation and colour. *Journal of Experimental Psychology: Human Perception and Performance.* In press.

3.0.1: Abstract

Four experiments examined the effects of pre-cues on visual search for targets defined by a colour-orientation conjunction. Experiment 3.1 showed that cueing the identity of targets enhanced the efficiency of search. Cueing effects were stronger with colour than with orientation cues, but this advantage was additive across array size. Experiment 3.2 demonstrated that cueing effects interacted with bottom-up segmentation processes while Experiment 3.3 showed the stronger effects of colour cues remained in a compound task. Experiment 3.4 confirmed the enhanced effect of colour cueing even when verbal rather than visual cues were used. The targets used were balanced for search efficiency within both orientation and colour dimensions. I suggest search benefits from the top-down cueing of colour compared with orientation, as colour cueing enhances the segmentation of displays into colour groups more efficiently. This enables search to an appropriate colour group to be initiated earlier. I discuss how top-down segmentation processes interact with differences in bottom-up segmentation to further improve target detection.

3.0.2: Introduction

In everyday life we often have to search scenes to find targets on the basis of some known feature – for example their colour or their shape (as when we look for a friend in a crowd). In a laboratory setting the processes underlying these behaviours have been studied through visual search tasks. Typically a search target may appear at a random location amidst varying numbers of distractors, and the time taken to decide that the target is present or absent is measured. Over almost half a century or so, research using visual search has unearthed a plethora of experimental evidence on the impact of physical properties of items (bottom-up factors) on the efficiency with which targets are selected (see Wolfe, 1998, and Müller & Krummenacher, 2006, for reviews). More recently, however, experimenters have also examined how knowledge about which items are being searched for influences the search process. For example, search for targets can be influenced by the action that participants perform (Bekkering & Neggers, 2002) or by defining the target in terms of its action rather than its visual properties (Forti & Humphreys, 2008; Humphreys & Riddoch, 2001). Even when targets are defined by their visual properties, differential effects may arise according to whether different features are expected – for example, as I elaborate below, an expectation for a target defined by its colour may have a different effect than an expectation for a target defined by its orientation. Understanding how these different expectations influence search, and separating their effects from those of bottom-up factors, is important for developing complete accounts of the search process.

There is a substantial literature demonstrating that search for a target defined by its colour can be highly efficient, and elements defined by their colour may be searched preferentially in relation to stimuli defined along other dimensions. See 1.5.4 for details. Similarly in colour and orientation conjunction searches, both Zohary and Hochstein (1989) and Poisson and Wilkinson (1992) found that stimuli defined by colour were selected preferentially to those defined by orientation (outlined in 1.5.4.1). The role of top-down and bottom-up contributions to this search advantage have not been clearly separated however. For example, targets defined by colour differences relative to distractors may be found efficiently because there is rapid bottom-up organisation of elements into colour-based groups (see Braithwaite, Humphreys, & Hulleman, 2005), with colour differences between the groups serving to guide search to a target. Evidence consistent with this proposal comes from studies of so-called ‘subset search’. In subset search, participants may be presented with displays where, over trials, different numbers of distractors carry a shared feature. Search is typically more efficient when the target falls within the smaller of two groups of distractors than when it falls within the larger of the groups, and this effect is pronounced when the subsets are formed through colour-grouping (Bacon & Egeth, 1997; Egeth, Vrizi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995). On the other hand, Sobel and Cave (2002) found no preference for searching a colour-defined subset over one defined by the same orientation when both dimensions were highly discriminable, suggesting that search may be determined less by the dimension that a target is defined along than the discriminability of target and distractor elements within particular dimensions. Differences in discriminability within a dimension may also contribute to other findings where colour appears dominant in the bottom-up capture of attention – one example being when attention is captured by a distractor that is a singleton along a dimension that is irrelevant to the search task. Attentional capture is typically stronger for singletons defined along the colour dimension than for singletons defined by their orientation or shape (Theeuwes, 1992), but this may reflect variations in the feature values within the dimensions.

Other evidence points to colour having a strong effect on top-down guidance of search. One procedure used to examine this involved giving participants an item to hold in working memory while they search for a different target. Search for the target is affected by the appearance of the working memory stimulus in the search display (see Downing, 2000; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006), whereas there can be little effect of an initial cue that is not held in working memory (Soto et al., 2005, 2006). That is, the effect is due to top-down biases modulated through working memory rather than bottom-up priming from the initial appearance of a working memory cue. Soto et al.

(2005) varied whether the colour or shape/orientation of the item in working memory matched one of the search stimuli and found stronger effects from colour matching than from shape/orientation matching.

Using a different procedure, Müller, Reimann, and Krummenacher (2003) cued participants on a trial-by-trial basis as to whether the target in a forthcoming display differed from distractors along a particular dimension (colour or orientation), or particular values along each dimension (red vs. horizontal). Valid pre-cueing of the dimension that defined the target facilitated search, relative to when the dimensional cue was invalid. In addition to this, though, cueing a particular colour value also influenced search, while, in contrast, there were only modest effects of cueing a particular orientation value. Müller et al. proposed that, within the colour dimension, attention could be set for a particular feature value as well as for the dimension itself, while a top-down expectancy in the orientation domain could only be set for the dimension. On the other hand, Hodsoll and Humphreys (2005) provided evidence for top-down expectancies being set for targets whose orientations differed categorically from those of distractors (see 1.5.4.3). These findings suggest that expectations can be set for at least coarse categories of orientation.

Unfortunately, studies of top-down effects have rarely equated the stimuli for the saliency of targets along each dimension. As a consequence, any dominant effects of colour could stem from the greater discriminability of targets along that dimension in a given experiment, when compared with targets defined along other dimensions. Effects may disappear once targets defined along the different dimensions are defined as being equally discriminable (cf. Sobel & Cave, 2002).

In the present study, I set out to assess whether there is differential top-down guidance of attention from colour relative to orientation cues when any bottom-up differences in saliency were eradicated. To our knowledge, no previous studies have looked at featural cueing in conjunction search. The distractors of the search displays were the same across all the experiments, comprising blue vertical and green horizontal bars. The targets were defined in terms of the conjunction of features not present in each distractor – green vertical or blue horizontal bars. Participants were cued on a trial-by-trial basis as to either the colour or the orientation of the forthcoming target. To rule out bottom-up biases favouring colour over orientation-defined targets, the saturation of the two colours was varied in an initial series of studies until there was no difference in search efficiency for a colour-defined over an orientation-defined target (details in Chapter 2). Subsequently, I examined whether cueing a colour or orientation feature value for the target had any differential influence on selection (Experiment 3.1). In Experiment 3.2, I pitted the effects of the top-down cues for the target against bottom-up guidance produced by varying the numbers of each type of distractor to create different subsets for search. Experiment 3.3 tested for effects of cueing at a stage of response selection and Experiment 3.4 examined the generality of the results by contrasting verbal with visual cues.

Experiment 3.1: Differential Top-down Cueing of Colour and Orientation

3.1.1: Introduction

Experiment 3.1 matched the conjunction search task from Experiment 2.1.2 but preceded each display by a visual cue, either a colour circular patch (indicating the likely colour of the target), a white oriented line (indicating the likely orientation of the target) or a white circular patch (the neutral condition). The colour and orientation cues were valid on 80% of the trials to encourage participants to use the information provided. I assessed whether cueing participants about the feature value defining the target would facilitate search, and whether effects from cueing colour would be the same as those from cueing orientation.

3.1.2: Method

The Methodology matched that of the conjunction task in Experiment 2.1.2, except as outlined below.

Participants. Seventeen University of Birmingham students, six male, 11 female, aged between 18 and 24 (average age of 20.18) took part.

Stimuli. The search display was the same as in the conjunction task in Experiment 2.1.2. The pre-cue[1] was one of five stimuli: a blue patch, a green patch, a white horizontal bar, a white vertical bar and a white patch. Orientation cues were either horizontal or vertical white bars whose physical dimensions matched those of the stimuli used in the pilot study. Coloured and neutral patch cues were filled circles, all with the diameter of 3.5mm (0.35º). The same colour levels were used for cues and search stimuli and are outlined in Table 2.1.

Design. There were four main independent variables: cue validity (valid, neutral, invalid), cued dimension (colour, orientation), array size (7, 15) and target type (green vertical, blue horizontal, absent). The main dependent variable was the reaction time (RT) taken to indicate the presence or absence of the target. Response accuracy was also measured.

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[1] We use this term to indicate that a cue was presented prior to each trial.

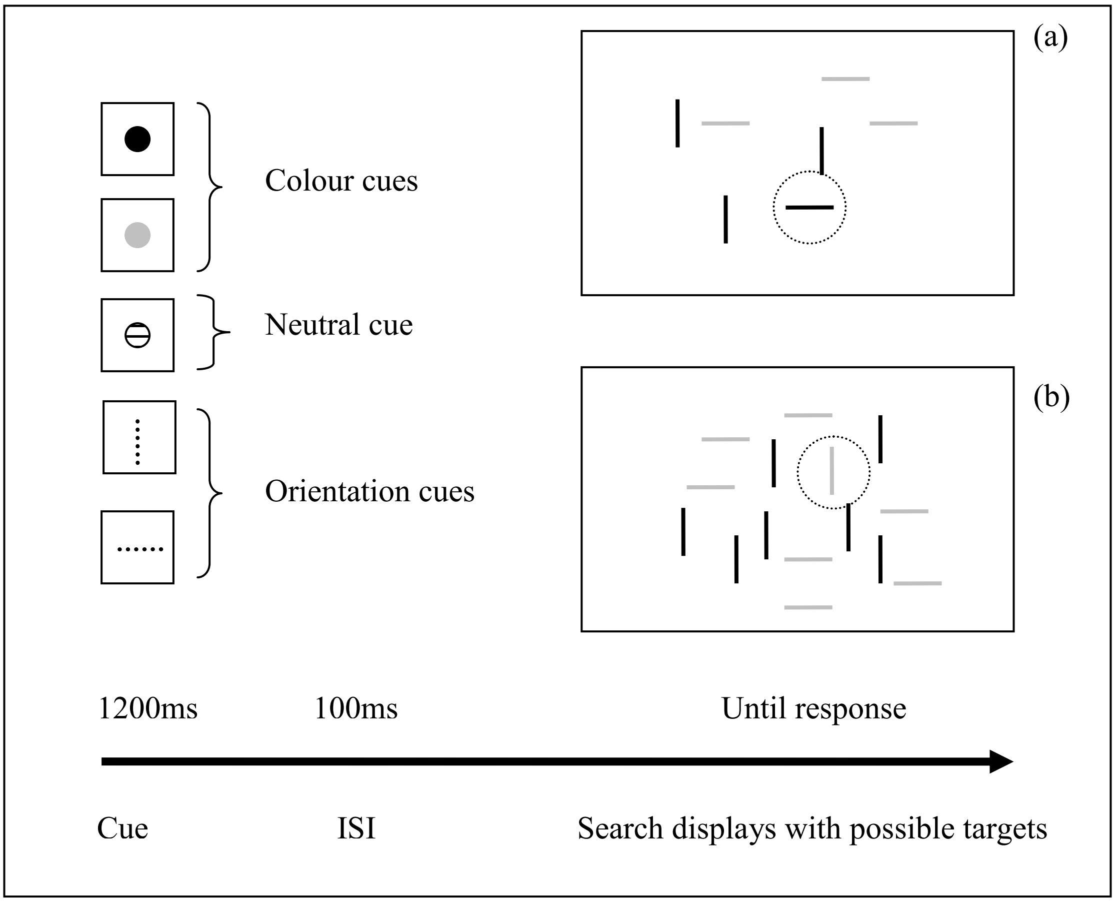

Figure 3.1. Simplified timeline of a trial from Experiment 3.1. Only one cueing stimulus was presented prior to each search array, with the colour and orientation cues predicting the feature of the following target. The two possible targets are shown (circled). The array size was either seven (Fig. 3.1a) or 15 (Fig. 3.1b). The stimuli were presented on a black background but for simplicity the background is shown here as white; blue stimuli are represented as black, green as grey and white as dotted/striped.

Procedure. As well as information about the nature of the targets, the instructions indicated the physical properties and predictive nature of the cue stimulus that was to be presented prior to each search. The cue was presented after the fixation cross for 1200ms and was followed by an inter-stimulus interval (ISI) of 100ms and arrays of either seven and 15 stimuli (see Figure 3.1). Due to high error rates during piloting, participants were informed about the nature of the targets prior to the experiment, with graphical representations of the target images presented adjacent to the monitor during the task. Targets were present for 62.5% of the trials (the bias was introduced as only target-present trials were of interest; target-absent trials just functioned to regulate the rate of anticipation responses, cf. Müller et al., 2003).

On one third of the target-present trials the cue predicted the colour of the target; on another third the cue predicted the target's orientation, while the cue was non-informative (neutral) for the final third of the trials. A green or blue patch was used to predict the target's colour, a white vertical or horizontal line predicted the target's orientation, while a white patch offered no prediction. The colour and orientation cues were valid on 80% of the trials and invalid on 20% (see Müller et al., 2003). Participants were informed that the majority of the cues were valid.

Participants took part in two one-hour sessions, each a minimum of 24 hours apart and consisting of four 96-trial blocks so that each participant undertook 768 experimental trials. All conditions were randomly interleaved in each identical block. At the beginning of the first session there was a block of 20 practice trials where data were not recorded, while at the beginning of second session there was a block of four practice trials.

3.1.3: Results

The data were cleaned as in Chapter 2 and pooled across the two orientation-cued conditions (horizontal and vertical) and, separately, across the two colour-cued conditions (blue and green), as well as across target type in each case (blue horizontal, green vertical). As target-absent trials were counted as catch trials, only target-present trials were analysed. For parsimony, I first analyse the neutral condition and then compare colour and orientation cueing effects in cost-benefit analyses relative to this baseline[2]. This procedure was followed throughout Chapter 3.

Neutral RTs. Median RTs for each participant and each condition were calculated. Group means are shown in Table 3.1. Analysis reflected a main effect of array size (F(1,16)=102, $p<0.001$, $\eta^2=0.865$), with RTs increasing with array size.

RT Cost-Benefits. To assess the relative magnitudes of the cueing effects, median RTs in the valid and invalid conditions were subtracted from those for neutral trials to create RT Benefits (on valid trials) and Costs (on invalid trials). Mean values are shown in Figure 3.2.

A three-factor ANOVA (array size, cue dimension, cue validity) revealed a reliable main effect of cue validity (F(1,16)=32.3, $p<0.001$, partial $\eta^2=0.669$) and a significant interaction between cue dimension and cue validity (F(1,16)=22.1, $p<0.001$, partial $\eta^2=0.580$). There was also a borderline significant array size x cue validity interaction (F(1,16)=5.1, $p=0.076$, partial $\eta^2=0.243$). However, the three-way interaction between array size, cue validity and cue dimension was not significant (F(1,16)=1.5, $p=0.492$, partial $\eta^2=0.083$). The array x validity interaction arose because the validity effects were larger at display size 15 than display size seven (520 vs. 382ms, both ps<0.001). The cue dimension x cue validity interaction emerged because the cueing effect was larger for colour cues (a validity effect of 548ms, $p<0.001$) than for orientation cues (a validity effect of 367ms, $p<0.001$). This was reflected in both increased benefits from colour cues on valid trials (the validity benefit was enhanced by 104ms) and increased costs on invalid trials (the costs increased by 76ms).

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[2] For details of raw RTs from cued trials see Anderson et al. (2010).

Accuracy. Accuracy effects followed RTs showing no speed-accuracy trade-off. See Table 2.2 for details.

	Array size			
Experiment	**7**		**15**	
	RT (ms)	Standard error	RT (ms)	Standard error (ms)
3.1	1252	68	1534	78
3.3	1991.9	79	2351	100
3.4			1626	115

Table 3.1. Means and standard errors from neutral, uncued trials in Experiments 3.1, 3.3 and 3.4.

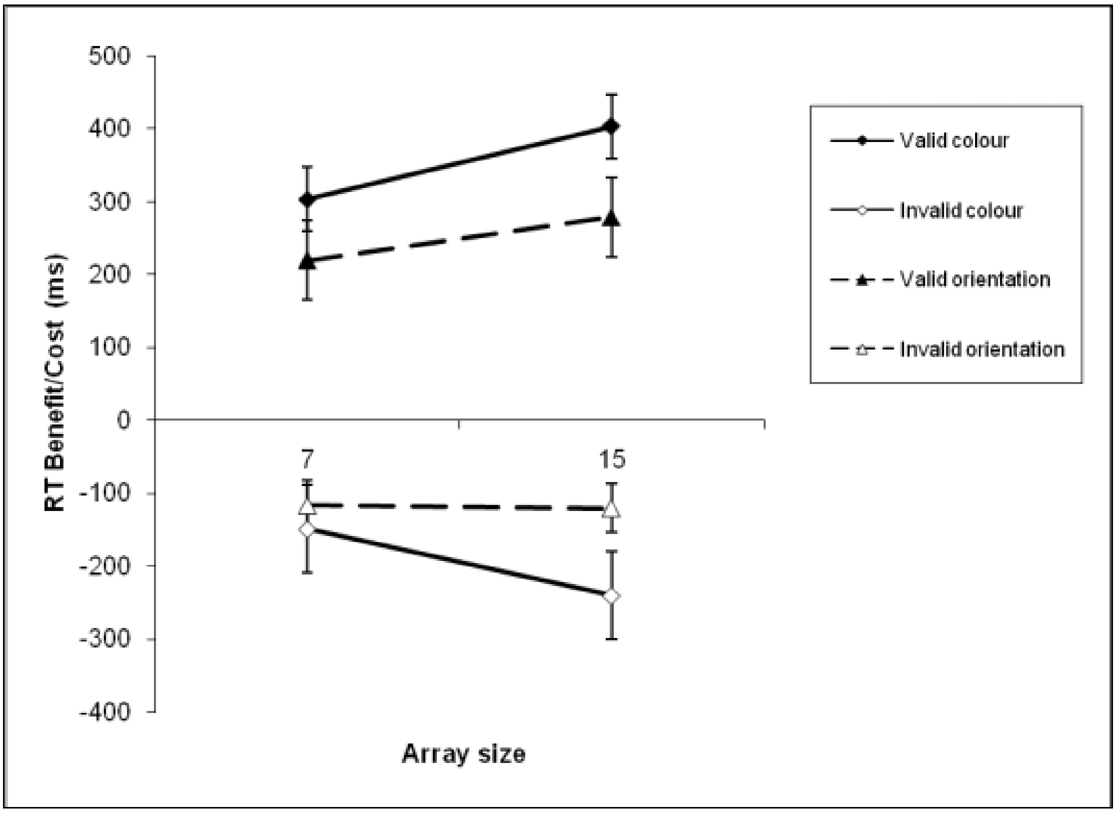

Figure 3.2. Means (+/- one standard error) of RT Benefits/RT Costs in Experiment 3.1, defined by cue dimension, cue validity and array size. A positive value indicates a benefit relative to the neutral condition while a negative value indicates a cost.

3.1.4: Discussion

The results demonstrate that valid cues facilitate search while invalid cues slow search. There was also a differential effect of the dimension that was cued – effects were larger following colour relative to orientation cues. It is interesting that this differential effect of cueing arose even though it was possible for participants to generate an expectancy of the other property of the target from the cue (e.g., given the cue 'blue' then the target's horizontal orientation could be predicted). However, if participants had generated an expectancy for both attributes then there should have been minimal differences between orientation and colour cues. The results suggest otherwise. I presume that the cognitive load involved in generating an expectancy of the other dimension from the cue mitigated against participants adopting this strategy. Alternately, participants could prioritise the cued feature (e.g., blue) above the other property of the target (e.g., horizontal), even though cues to guide attention were equally salient in the search displays. Attention would then be directed to stimuli matching the cue in the cued dimension before search would continue within this group for a disparity within the alternate dimension (Friedman-Hill & Wolfe, 1995).

Although both colour and orientation cues improved search rates, and although colour cues had a stronger overall effect on search, the improvements on search efficiency were equal for the two cue types. Thus the differential effect of colour cueing was on the intercepts rather than the slopes of the search functions. The effects of the cues generally on search efficiency can be explained if the cues bias participants to initiate search with a particular sub-group of distractors, while in neutral trials search operates randomly across all of the items present. Since the target will fall within the cued sub-group on valid trials, fewer items will on average need to be searched. In contrast, on invalid trials the target will fall within the sub-group searched second, slowing target detection relative to when a random search strategy is adopted (when the target will be detected on average after searching half of the items present). Since the type of cue affected the intercepts rather than the slope of the functions, it appears that the likelihood of search being biased to a given sub-group, following a cue, was equal for colour and orientation cues. The differential effect of cue-type must thus come about for a different reason. I suggest at least two possibilities. One is that the two cue types have a differential impact on the time taken to segment the search display into colour or orientation-coded sub-groups. If colour cues exert a stronger influence on the initial segmentation process, then the time to start search of the cued sub-group will be faster following colour relative to orientation cues. However, while this should lead to faster overall RTs, it is not clear why costs should be greater after colour compared with orientation cues unless some other factor is involved. For example, it might be that the faster the assignment of attention to one sub-group, the slower the re-assignment of attention to the second sub-group when the cue is invalid – a type of 'first-in, last-out' process.

A second possibility is that colour and orientation cues have differential effects on a late stage of response selection, so the target-present response is assigned more rapidly to a colour cued target compared to an orientation-cued target. For example, a decision criterion might be pushed more towards the expected target value after a colour cue. This would speed responses when the target matches the expectation, but it would also slow responses on trials when the target has the other colour value (when the colour cue is invalid) – on invalid trials, the decision criterion would be further away from the actual value of the target. These two possibilities were explored in Experiments 3.2 and 3.3 here. Experiment 3.2 contrasted the effects of directing attention from a cue with the effects of bottom-up segmentation, introduced by including in displays subsets of distractors with particular feature values. Search may be directed in a bottom-up manner to a subset of distractors having a minority feature in the display (cf. Bacon & Egeth, 1997). How does cueing the dimension and feature value of the target interact with this bottom-up directing of attention? For a late, response-selection account of the cueing effects, any effects due to bottom-up directing of attention to a subset of items should be additive with the cueing effect, since the cueing effect emerges only at a response assignment stage. On the other hand, if the cue itself affects display segmentation and directs attention to a relevant subset of items, then it may interact with bottom-up factors that generate subset search. For example, the normal direction of attention to a minority group of distractors (cued bottom-up) may be overruled when the cue directs attention to another sub-group of items. Experiment 3.3 introduced a compound search task, so response assignment could be divorced from attentional selection of the target. Effects of the cue on response selection should be eliminated when a compound search task is carried out.

Experiment 3.2: Cueing And Bottom-up Subset Search

3.2.1: Introduction

In Experiment 3.2, I varied the ratio of the different types of distractor in the conjunction search task, creating conditions that should induce subset search (e.g., Bacon & Egeth, 1997; Sobel & Cave, 2002). Using the same stimuli as Experiment 3.1, I introduced three ratio conditions, two with unequal numbers of each type of distractor and one where the ratios were balanced (as in Experiment 3.1). In the uncued, neutral condition, I expect to find subset search effects, with RTs being reduced when the target is in the minority set of distractors. (i.e., there should be a smaller-group bias, Sobel & Cave, 2002). In the cue conditions I assessed whether this bottom-bias to the smaller distractor group was modulated by the cue.

3.2.2: Method

The methodology of Experiment 3.2 was the same as that of Experiment 3.1 unless indicated below.

Participants. There were 20 University of Birmingham students, seven male, 13 female, aged between 18 and 26 (average 20.58). Two participants were removed due to an overall accuracy level of less than 90%.

Design. There were four main independent variables: cue validity (valid, neutral, invalid), cue dimension (colour, orientation), distractor ratio (see Procedure section) and target type (green vertical, blue horizontal, absent).

Procedure. Participants took part in two one-hour sessions, each consisting of three 144-trial blocks so that each participant undertook 864 trials, with all conditions randomly interleaved in each block. At the beginning of the first session there were 20 practice trials where RTs and accuracy was not recorded, while at the beginning of the second session there was a block of four practice trials.

The procedure replicated that of Experiment 3.1 apart from two alterations: the array size was always 15 and the ratio of distractors was manipulated as follows: three blue vertical bars (BV) and 11 green horizontal bars (GH; see Figure 3.3a); 7GV and 7GH (Figure 3.3b, ratio matches that in array size 15 for Experiment 2.1); and 11BV, 3GH (Figure 3.3c).

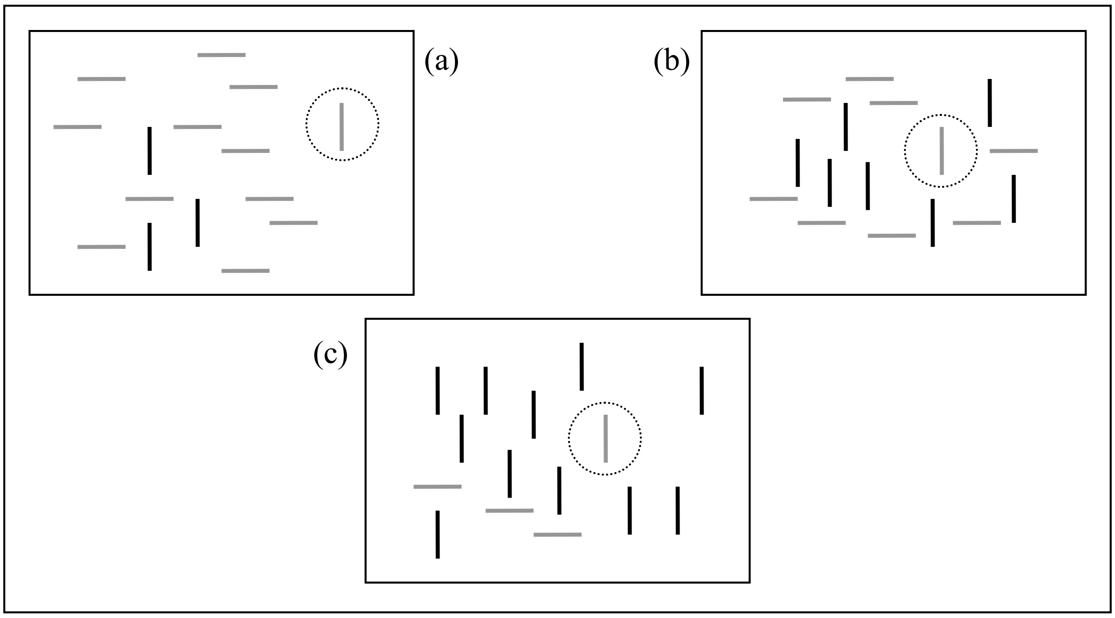

Figure 3.3. Examples of the three conditions in Experiment 3.2. Stimuli were presented on a black background, but for clarity it is shown here as white; green stimuli are presented as grey, blue as black. The examples only have green vertical targets; however it was equally likely for the target to be a blue horizontal bar.

3.2.3: Results

The data were cleaned as in Experiment 3.2. Target-absent trials were considered catch trials so were not analysed. Therefore, median RTs from target-present trials in each condition for each participant were calculated as Experiment 3.1, although instead of array size the data were separated by distractor ratio.

*RTs: Neutral trials***.** Performance was examined in the neutral condition to assess bottom-up effects reflecting subset search. Mean RTs across participants are shown in Figure 3.4. A two-factor ANOVA was conducted with the factors being target type (blue horizontal vs. green vertical) and distractor ratio ((a) 3BV, 11GH; (b) 7 BV, 7GH; (c) 11BV, 3GH. See Figure 3.4). There was a main effect of target type (F(1,17)=14.4, p=0.002, partial η^2=0.459), with longer RTs for the blue horizontal target. There was also a reliable effect of distractor ratio (F(2,34)=6.6, p=0.008, partial $\eta^2=0.279$). The ratio analysis showed the U-shape typical of a ratio experiment, with RTs to displays with unequal ratios (a) and (c) being shorter than those to displays with equal numbers of each type of distractor (b) ($p<0.001$, $p=0.046$ respectively). There was also an interaction ($F(2,34)=5.5$, $p=0.018$, partial $\eta^2=0.244$). The difference between RTs to the two targets were reduced for display type (c) (a difference of 157ms, $p=0.14$) compared to that in both display type (a) (a difference of 320ms, $p<0.001$) and display type (b) (a difference of 330ms, $p=0.002$).

I also investigated the effect on behaviour of smaller subsets defined by colour or orientation compared with when these factors were balanced. To analyse the effect of a smaller colour subset, I calculated the difference in RTs between displays (a) and (b) for trials with a blue vertical target and between (c) and (b) for trials containing a green horizontal target and vice versa for the orientation-defined subset. A two-factor ANOVA (subset dimension, target type) showed that there were borderline main effects of subset dimension ($F(1,17)=5.8$, $p=0.066$, partial $\eta^2=0.24$) and target type ($F(1,17)=5.8$, $p=0.056$, partial $\eta^2=0.254$), with the ‘subset effect’ larger for orientation compared to colour (119ms vs. 37ms).

These results indicate that there were bottom-up effects of subset search, with search being faster when there were unequal ratios of distractors than when the ratios were equal. Interestingly this bottom-up effect seemed to be strongest within the orientation rather than the colour dimension. Note that search for the green vertical target was fastest when the smaller group contained 3BV distractors and search for the blue horizontal target was fastest when the smaller group contained 3GH distractors.

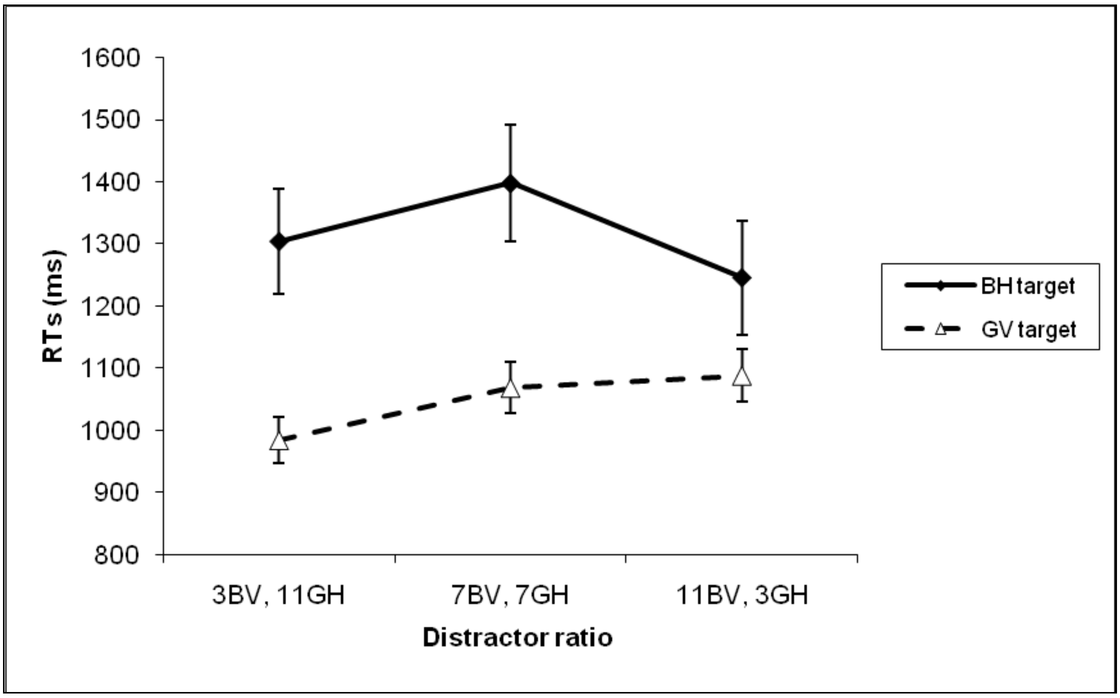

Figure 3.4. Mean (+/- one standard error) of median RTs from the neutral condition in Experiment 3.2, separated by distractor ratio (BV = blue vertical stimulus, GH = green horizontal stimulus) and target (BH = blue horizontal stimulus, GV = green vertical stimulus).

RT Cost-Benefits. For the cued data, I re-categorised the distractor ratio depending on the cue. Trials where the cued feature matched that defining the smaller distractor subset were coded as the Small cued group, while trials with the cue feature matching that shared by the larger distractor subset were included in the Large cued group condition (see Table 3.2). The coding for trials with 50:50 ratios was unchanged, but they were labelled as the Equal cued condition.

		Display type		
Target	**Cue**	**Small group cued**	**Equal group cued**	**Large group cued**
BH	Valid blue	(a) 3BV, 11GH	(b) 7BV, 7GH	(c) 11BV, 3GH
GV	Valid green	(c) 11BV, 3GH	(b) 7BV, 7GH	(a) 3BV, 11GH
BH	Invalid green	(c) 11BV, 3GH	(b) 7BV, 7GH	(a) 3BV, 11GH
GV	Invalid blue	(a) 3BV, 11GH	(b) 7BV, 7GH	(c) 11BV, 3GH
BH	Valid horizontal	(c) 11BV, 3GH	(b) 7BV, 7GH	(a) 3BV, 11GH
GV	Valid vertical	(a) 3BV, 11GH	(b) 7BV, 7GH	(c) 11BV, 3GH
BH	Invalid vertical	(a) 3BV, 11GH	(b) 7BV, 7GH	(c) 11BV, 3GH
GV	Invalid horizontal	(c) 11BV, 3GH	(b) 7BV, 7GH	(a) 3BV, 11GH

Table 3.2. An outline of how the original displays (a), (b) and (c) (see Figure 3.3) were re-coded into display condition in Experiment 3.3. Displays were categorised depending on the cue, so that the Small group cued indicated a display where the smaller group of stimuli shared the cued feature; the Large group cued indicated that the larger group of stimuli shared the cued feature. The target and array stimuli in each condition are indicated as follows: BH = Blue Horizontal, GV = Green Vertical, BV = Blue Vertical, GV = Green Vertical. No such coding was necessary when the Equal group of distractors was cued.

The relative effects of cueing by colour and by orientation were examined by subtracting RTs in each cueing condition with RTs on neutral trials, with the Small group and Large group cued defined as in Table 3.2, according to the assumed attribute of the target that would be used to guide search in the cueing condition. Means are shown in Figure 3.5.

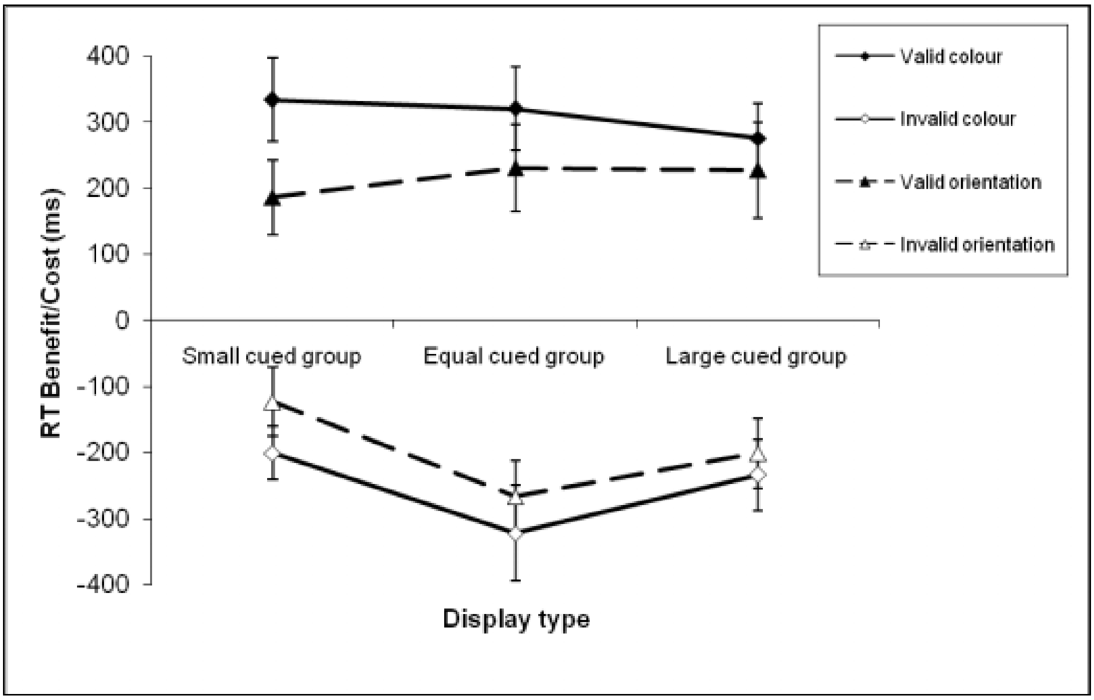

Figure 3.5. Means (+/- one standard error) of RT Benefits/Costs from Experiment 3.2, separated by display type, cue validity and cue dimension.

A three-factor ANOVA (display type, cue dimension, cue validity) revealed a main effect of validity (F(1,17)=35.1, p<0.001, partial η^2=0.673) as well as significant interactions between cue dimension and cue validity (F(1,17)=13.4 p=0.004, partial η^2=0.442) and display type and cue validity (F(2,34)=8, p=0.002, partial η^2=0.318). The cue dimension x cue validity interaction was due to a larger modulation of performance by colour cueing (571ms vs. 386ms); there were both larger RT Benefits (p=0.002) and larger RT Costs (p=0.048) on colour-cued trials. The display type x cue validity interaction was unpacked by assessing the effect of cueing (RT Benefit minus RT Cost) for each display type (the main effect of validity was reliable in all cases, all p<0.001). A two-factor ANOVA (cue dimension, display type) showed that there were main effects of cue dimension (F(2,34)=8, p=0.002, partial η^2=0.318) and display type (F(1,17)=35.1, p<0.001, partial η^2=0.673). However, the significant effect of display type showed that the original interaction was driven by a significantly larger effect of validity at the Equal group cued condition compared to the Small group cued (p=0.008) and a trend towards significance compared to the Large group cue (p=0.17). However, there was no difference between the validity effects for the Small and Large group cued conditions (p=0.928).

Overall, the data show that the larger modulation by colour cueing was not affected by the number of stimuli matching the cued feature. While the effect of cue validity was largest at a 50:50 distractor ratio, there was no difference in effect size between cueing three or 11 stimuli.

Accuracy. There was no speed-accuracy trade-off with accuracy largely following the pattern of RTs. See Table 2.2 for details.

3.2.4: Discussion

Experiment 3.2 replicated the effects of feature cueing on search, generating substantial costs and benefits on trials where the cues were valid or invalid, respectively. In this case, the effects occurred in the context of bottom-up cueing of attention to unequal-sized distractor groups, enabling me to examine the interaction between the cues and bottom-up segmentation processes.

In the neutral condition, there was evidence for bottom-up segmentation affecting performance, with performance being faster when there were unequal ratios of distractors relative to when there were equal numbers of each type of distractor. Interestingly, performance appeared to be more affected by segmentation into elements grouped by orientation, since the advantage for targets appearing in the minority group was particularly strong when group size was defined on the orientation rather than the colour dimension. This occurred even though I matched the saliency of the individual items (see Experiment 2.1.2). The advantage for orientation may arise because bottom-up grouping based on orientation was stronger than bottom-up grouping based on colour here (cf. Sobel & Cave, 2002).

There was also an interaction between the bottom-up bias for attention to be drawn to the smaller subset, and top-down cueing. This is revealed by larger effects of cue validity for displays with an equal ratio of distractors than for displays with unequal ratios of distractors. The change in the cue validity effect was most marked for invalid trials, with the cost of invalid cueing being reduced when there were unequal distractor ratios. This suggests that, although the cue guided search, participants were able to switch more rapidly to the uncued group when there was an unequal ratio of distractors. This may be illustrated most easily in relation to displays (a) and (c) shown in Figure 3.3, when a green vertical (GV) target is present. On a valid colour cue trial (green), the cue might relate to the small group (display c) or to the large group (display a). On an invalid colour cue (blue) trial the cue might relate to the large group (display c) or the small group (display a). The cost of cueing might be reduced on invalid trials when attention is directed to the small group (display a) because this can be quickly rejected and search re-directed to the group containing the target. When attention is directed to the large colour group (display c), the presence of a small orientation group, segmented from bottom-up cues, allows attention to be switched more rapidly than when the distractor groups are equal in size (and note that the target, when present in this small group, will tend to have relatively high salience against the small number of distractors with a matching attribute). This also suggests that bottom-up segmentation might have operated in parallel with any segmentation induced by the top-down cue. For example, the top-down colour cue might induce segmentation into colour groups, but the parallel segmentation into a small and large orientation group allows attention then to be switched to the small orientation group, when the target is a member of that group (cue green to the GV target in display a).

As in Experiment 3.1, the effects of cueing colour were stronger than those of cueing orientation. This may be because the colour cue can initiate segmentation in a top-down manner more quickly than any top-down induction of segmentation by orientation. On the other hand, if the contrasting cue effects were due to differences at a response stage, then the cueing effects should have been additive with changes in the distractor ratio. There should only have been bottom-up guidance of search to the smaller group, followed by more rapid selection of the response to colour. Critically, the costs and benefit of cueing should have been equal for displays with equal ratios of distractors and for displays with unequal distractor ratios. It was not. In Experiment 3.3, I sought to provide a further direct test of the response effect account by presenting participants with a compound search task.

Experiment 3.3: Compound Search

3.3.1: Introduction

Recently, Theeuwes et al. (2006) presented evidence that intra-trial cueing – the presenting of a cue between consecutive trials – of a target's features can influence performance at the level of response selection. Using a verbal cue to predict the dimension defining the target of a feature-singleton search (cf. Müller et al., 2003), they found effects of cue validity when the response decision was present-absent, but none when the decision was irrelevant to the search task. They suggested, therefore, that cueing affected processes at the response level of visual selection, rather than early top-down modulation of attention (see 1.4.3). The stronger effects of colour than orientation cueing, in Experiments 3.1 and 3.2, could be because colour cues shift the decision criterion so that it is lowered for the expected colour and raised for the unexpected colour (on invalid cue trials). The net result would be that the costs and benefits from colour cueing are stronger than those from orientation cueing (see also Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997; for similar arguments from cueing effects on search). Experiment 3.3 used a compound task rather than having participants simply respond whether a target was present or absent. With a compound task the features of the target and the cue are independent from the response-defining feature. Hence, the cues cannot modulate the links between the selected feature and response selection. If the differential effect of colour and orientation cueing was due to an effect on response selection, then I expect the effect to be eliminated here.

3.3.2: Method

The methodology was identical to that of Experiment 3.1 unless indicated below.

Participants. Eighteen University of Birmingham students, four male, 16 female, aged between 18 and 33 took part (average age 24). One participant was removed due to unusually slow responses.

Design. There were four main independent variables: cue validity (valid, neutral, invalid), cue dimension (colour, orientation), array size (seven or 15 items) and target type (blue horizontal, green vertical). The main dependent variable was the RT taken to indicate which feature the target contained (+ or x). Accuracy was also measured.

Stimuli. Search items matched those used in the conjunction task in Experiment 2.2.

Procedure. Participants took part in a one-hour session, consisting of five 80-trial blocks, so that each participant undertook 400 trials. Trial conditions were randomly interleaved within each block with the first block regarded as practice where RTs and accuracy were not recorded.

The procedure replicated that of Experiment 3.1 except that the participant's response depended on the symbol on the target stimulus (whether an x or + was present), not whether the target was present or absent. Consequently there were no absent trials. Half the participants responded to the presence of '+' with their dominant hand, the other half responded to 'x', pressing the 'Z' or 'M' keys depending on handedness. Signs were present on the computer monitor to remind participants of the targets and which key response corresponded to which symbol.

3.3.3: Results

RTs. The data were collated as in Experiment 3.1 except that RTs were also pooled across action-defining features (e.g., + and x).

Neutral RTs. The mean and standard error of the participants' median RTs on neutral trials are shown in Table 3.1. As suggesting by the data, RTs increased with larger array sizes ($F(1,17)=43.188$, $p<0.001$, $\eta^2=0.726$).

RT Cost-Benefits. RT Benefits and Costs were calculated as in Experiment 3.1. The resulting data are depicted in Figure 3.6. There was a main effect of validity ($F(1,16)=59.6$, $p<0.001$, partial $\eta^2=0.788$) and a reliable interaction between array size and cue validity ($F(1,16)=23.4$, $p<0.001$, partial $\eta^2=0.595$), a borderline significant cue dimension x cue validity ($F(1,16)=5.6$, $p=0.062$, partial $\eta^2=0.258$). The former interaction arose because the validity effects were smaller at display size seven than at display size 15 (857ms vs. 1524ms, both $p<0.001$). The dimension x validity interaction was due to the validity effects being larger following colour relative to orientation cues (1288ms vs. 1093ms, both $p<0.001$). This advantage for colour cueing did not interact with the array size.

Accuracy. The results showed no speed-accuracy trade-off. See Table 2.2.

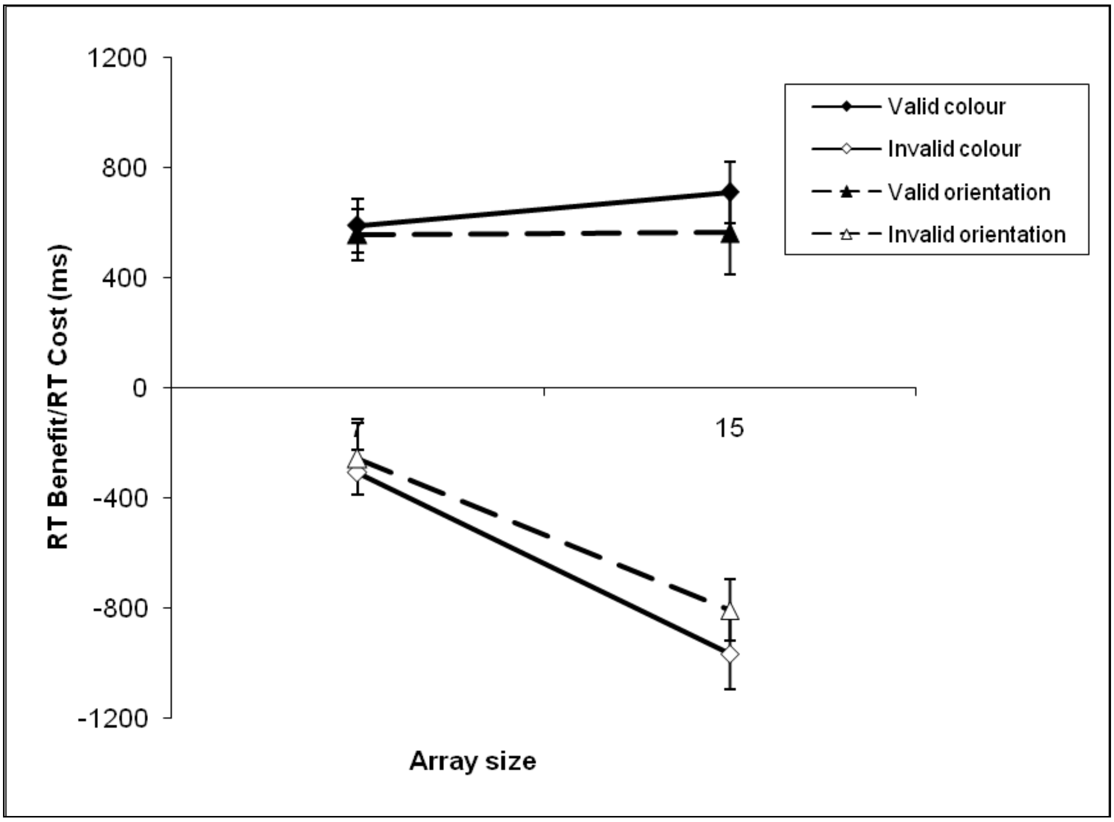

Figure 3.6. Means (+/- one standard error) of RT Benefit/RT Cost from Experiment 3.3, defined by cue dimension, cue validity and array size.

3.3.4: Discussion

The results replicated the cueing costs and benefits found in Experiments 3.1 and 3.2 – there were strong effects of the cues, cue validity affected search rates, and cueing effects overall were greater for colour than for orientation cues. The differential effects of colour over orientation cues remained additive with the effects of the display size.

These results contradict the proposal that the asymmetrical effects of colour and orientation cues are due to colour having a greater influence on shifts in response criteria. In a compound task, response assignment is independent of the dimension used to select the target, preventing the dimension from differentially influencing response selection. Despite this, greater effects of cueing emerged with colour cues. This result strongly points to the asymmetrical cueing effects reflecting an earlier process involved in parsing the display and guiding search to colour- or orientation-defined groups. In Experiment 3.2, I presented evidence that, in the neutral baseline condition, bottom-up biases in segmentation favoured orientation-defined targets. This bias appears to be overridden when a colour cue is presented, with the result that the initial parsing is into colour groups and search is directed into the colour group indicated by the cue. The overall outcome is that a larger effect of colour cueing emerges.

In the final experiment, I assessed two issues. First, whether the differential effect of colour cueing was indeed top-down in nature. When visual cues are used, it is not clear if cueing effects occur in a top-down or bottom-up manner, since bottom-up effects may arise on the basis of perceptual priming from the colour or orientation values present in the cues. To eliminate bottom-up effects Experiment 3.4 was conducted using verbal cues. Top-down effects may survive this switch in cue type (see Soto & Humphreys, 2007), whereas bottom-up effects may not. Second, I appraised whether the supposedly ‘neutral’ stimulus used in the baseline condition biased performance. The stimuli used was a filled white circle and as this item has a colour but no orientation, it remains possible that it was not an ideal baseline for both colour and orientation cueing. Instead, in Experiment 3.4, no pre-cue was presented on neutral trials, thereby removing stimulus-drive bias.

Experiment 3.4: Visual vs. Verbal Cueing

3.4.1: Introduction

A number of studies (e.g., Maljkovic & Nakayama, 1994; Kristjánsson, Wang, & Nakayama, 2002; Kristjánsson, 2006; Olivers & Meeter, 2006) have found that the repetition of identical target stimuli, across trials, facilitates search compared to when the target changes. This perceptual priming has largely been attributed to bottom-up processes from stimulus repetition, processes that could be involved in the cueing effects found previously in our research. Indeed, Wolfe, Horowitz, Kenner, Hyle and Vasan (2004) replicated the facilitation of priming using an inter-trial stimulus cue that matched the following search target. Experiment 3.4 compared the effects of visual (colour patch, line orientation) and verbal cues. With verbal cues, bottom-up priming within the same trial should be minimised.

In the prior experiments outlined here, the physical nature of the neutral cue may also have biased search. The stimulus used – a white filled circle – possessed colour attributes while orientation information was absent. Previous studies have shown that information associated with a pre-cue also affecting search (e.g., Moores, Laiti, & Chelazzi, 2003; Huettig & Altman, 2005; Soto et al., 2005). It may therefore be that the neutral cue may not be suitable to be used as a baseline for both colour and orientation cues. Instead, the neutral condition in Experiment 3.4 included no pre-display stimulus, so that an unbiased baseline measure could be obtained.

3.4.2: Method

Experiment 3.4 used a similar methodology to Experiment 3.3, with the differences outlined below.

Participants. Eighteen University of Birmingham students, five male, 13 female, aged between 19 and 41 (average age 24.28) took part.

Stimuli. Response-decisions were identical to those used in Experiment 3.3, while the array stimuli differed only in size from Experiments 3.1-3.3. The bars matched those used in Experiment 2.3. Colour levels are outlined in Table 2.1.

Trials were separated into visual-cued, verbal-cued and neutral blocks. In the visual-cued block, the cues were identical to those used in previous experiments (colour patches, lines of a particular orientation). In the verbal-cued conditions, these stimuli cues were replaced with the words *blue*, *green*, *horizontal*, and *vertical*. The words were presented in capitals in white, Arial type, with a height of 7mm (0.67°) and width varying from 26mm (2.48°; 'BLUE') to 64mm (6.11°; 'HORIZONTAL').

Design. There were four main independent variables: cue type (verbal, visual), cue validity (valid, neutral, invalid), cue dimension (colour, orientation) and target type (blue horizontal, green vertical). The main dependent variable was the RT taken to indicate which feature the target contained (+ or x). Accuracy was also measured.

Procedure. Participants took part in a single one-hour session, with three blocks of trials. Each block was made up of either neutral, visual-cued or verbal-cued trials with the order counterbalanced over participants. Neutral trials were different to those of previous experiments, with no cue presented. Visual cues were unchanged from Experiment 3.4. The timeline of verbal-cued trials was identical to that of the visual-cued trials. However, the blue patch stimulus was replaced with the word 'BLUE'; the green patch with 'GREEN'; the white horizontal line with

'HORIZONTAL'; and the white vertical line with 'VERTICAL'. Validity did not differ between cued blocks, but instructions were altered to indicate the differing natures of the cues. The neutral block was 60 trials long, with 10 practice trials preceding the block. Cued blocks each consisted of two blocks, one word and one stimulus cued, of 80 trials with 15 practice trials at the beginning of each block.

3.4.3: Results

RTs. Data was collected as in Experiment 3.4, except RTs were separated by cue type (e.g., visual or verbal) rather than array size. As there was a single neutral condition, this could not be analysed (see Table 3.1 for the group mean).

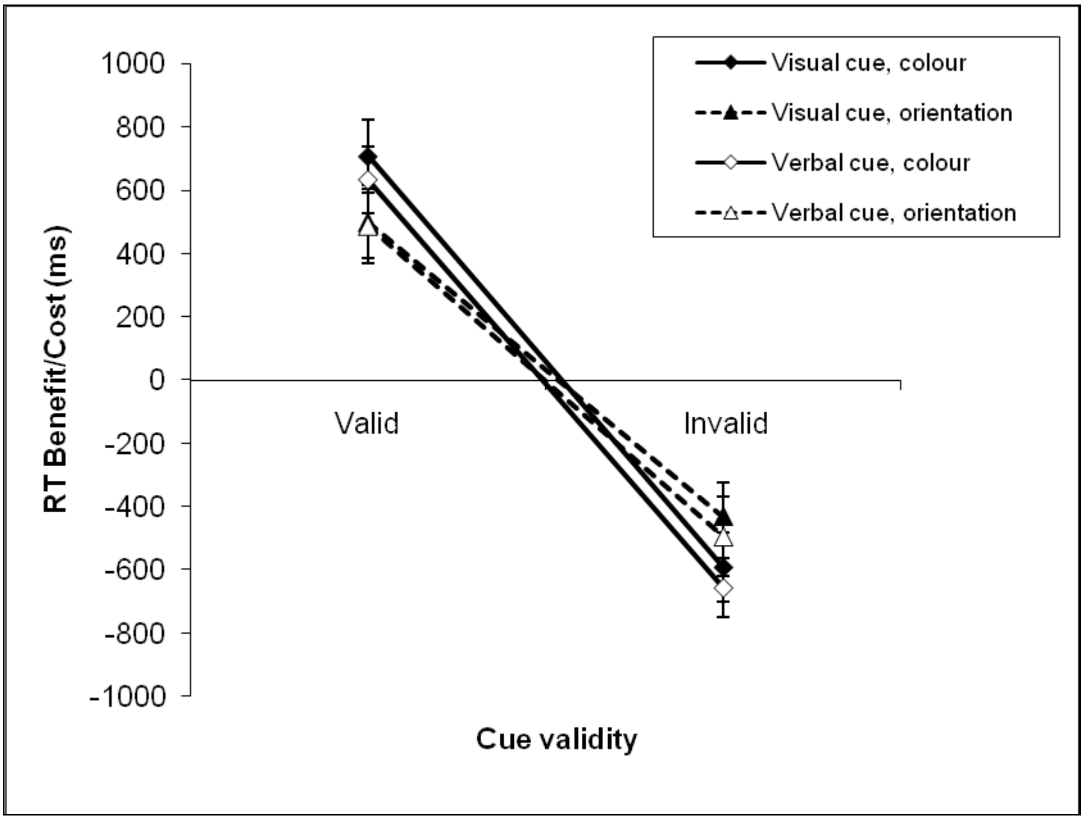

Figure 3.7. Mean RT Benefits/Costs (+/- one standard error) from Experiment 3.4, defined by type of cue (visual or verbal), dimension cued (colour or orientation) and cue validity (valid or invalid).

RT Cost-Benefits. To compare the effect of verbal and visual cueing, RT Benefits and RT Costs were calculated by subtracting median valid and invalid RTs from the corresponding median RTs from the neutral block (as in Experiments 3.1-3.3). Mean values are shown in Figure 3.7.

A three-factor ANOVA (cue type, cue dimension, cue validity) showed no effects of cue type (whether the cue was visual or verbal; $F(1,17)=1$, $p=0.64$, partial $\eta^2=0.058$). There was a main effect of cue validity ($F(1,17)=81.9$, $p<0.001$, partial $\eta^2=0.828$) and an interaction between cue dimension and cue validity ($F(1,17)=9.9$, $p=0.012$, partial $\eta^2=0.367$), with larger modulation of behaviour by colour (1294ms, $p<0.001$) compared to orientation cues (957ms, $p<0.001$).

RTs: Quartile analysis. Although the analysis showed no difference between visual and verbal cues it is possible that this masks the presence of contrasting time courses to the effects. For example, visual cues might exert an earlier effect than verbal cues due to bottom-up priming of the perceptual system before the search display appears. To assess this, I separated early and late RTs based on fastest and slowest scores (e.g., the 25th and 75th RTs) for each participant in each condition. I then compared the cueing effects for the fast and slow search times (see also Soto et al., 2005, for a similar approach). Due to small number of trials with invalid cues, only valid RTs were used in the analysis.

RT Benefit: Quartile analysis. The cueing effect was calculated for all conditions by subtracting the quartile score from valid trials from the corresponding score from neutral, uncued trials. As the fast and slow quartile scores were not independent, they were analysed separately. Means are shown in Figure 3.8, with the mean of median RTs included for visual comparison.

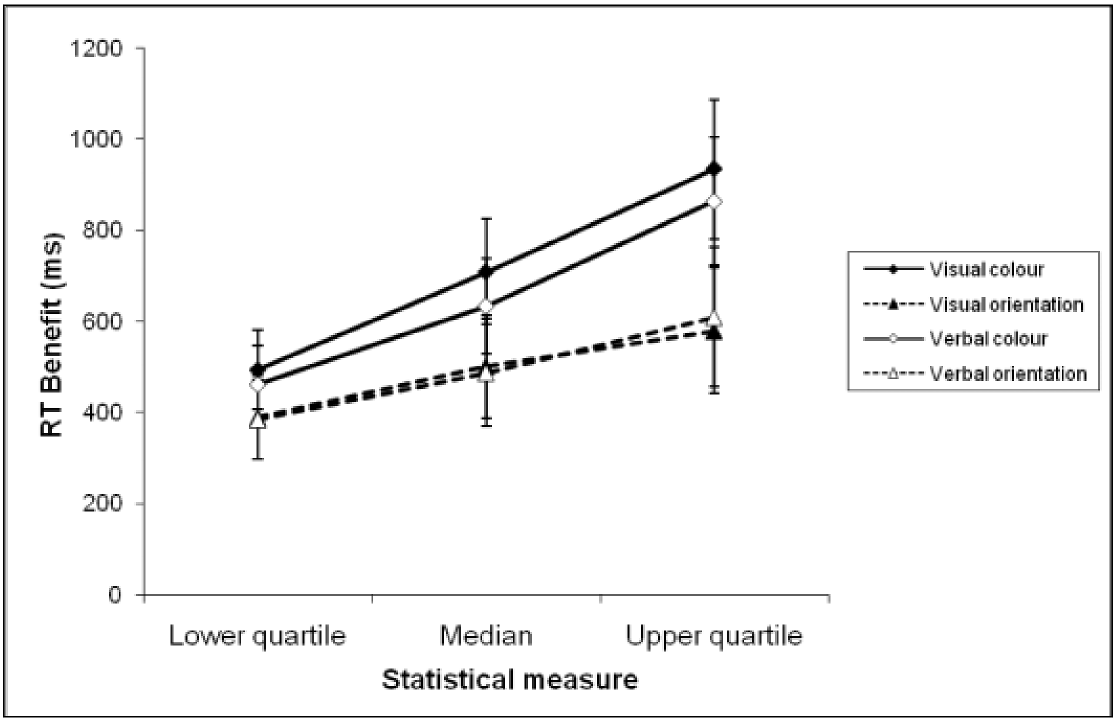

Figure 3.8. Means (+/- one standard error) of RT Benefit on the fastest (lower quartile), median and slowest (upper quartile) RTs from valid cueing in Experiment 3.4, defined by type of cue (visual or verbal) and dimension cued (colour or orientation).

RT Benefit: Fastest quartile. A two-factor ANOVA (cue type, cue dimension) found a main effect of cue dimension (F(1,17)=11.7, p=0.006, partial η^2=0.408) with a larger benefit from colour compared to orientation cues. No other effects or interactions reached significance (Fs<1)

RT Benefit: Slowest quartile. Analysis again found a main effect of cue dimension (F(1,17)=17.5, p=0.002, partial η^2=0.508), with colour cueing leading to a larger benefit than orientation cueing, but no main effect of cue type (F<1). There was a trend towards an interaction, but this did not reach significance (F(1,17)=2.8, p=0.22, partial η^2=0.143).

3.4.4: Discussion

Experiment 3.4 showed that the pattern of effects from stimulus cueing remained the same when the predictive information was delivered by verbal cues as when it was provided by a visual cue, with a larger modulation of selection by colour than by orientation cues. The data also demonstrated the colour advantage occurred irrespective of the nature of the neutral baseline. Further to this, the pattern remained consistent across the RT distribution indicating that the underlying processes occur early on during search. These results go against the hypothesis that the advantage for colour cueing found in Experiments 3.1-3.3 was merely a consequence of perceptual priming by the physical nature of the visual cues. Instead, the data are consistent with the processes involved in the dimensional difference being top-down in nature. Indeed, the RT quartile analyses indicated that effects of verbal cues affected both the fastest and slowest RTs similar to the visual cues. There was no evidence for bottom-up priming from visual cues.

3.5: General Discussion

I have reported four experiments showing robust effects on search from pre-cueing the likely feature of the following target. In Experiment 3.1, I showed that the effects of cueing attention to the likely colour of the target had a greater overall effect on performance than cueing attention to the likely orientation of the target. The enhanced effect of colour cueing was additive across display size, although both colour and orientation cueing effects increased at the larger display size. This additive effect of the cue type and display suggests that the type of cue either influenced an early segmentation process, prior to search being initiated, or a late process of response selection. In Experiment 3.2 the effects of the cue were examined in combination with bottom-up influences on segmentation and attentional guidance. In the neutral baseline, search was facilitated when uneven ratios of distractors were presented consistent with bottom-up biases affecting performance. Despite the presence of these bottom-up biases when there were unequal distractor groups, cueing still affected performance. The effects of cueing were reduced, however, when there were unequal numbers of distractors in the displays, with the costs from invalid cueing reducing in magnitude. This result suggests that bottom-up segmentation took place in parallel with any top-down induced segmentation, making it easier to switch attention to a small group coded through bottom-up segmentation when invalid cues directed attention to the larger of the two groups present. Experiment 3.3 tested whether the effects of cue type arose due to differential effects on setting the response criteria. I found no evidence for this. In a compound search task, the cue used to select the target is separated from the property used to select the response. This should reduce cueing effects at a response level. Despite this there remained greater effects from cueing colour than cueing orientation. Finally, Experiment 3.4 demonstrated that cueing effects were equally large from visual and verbal cues, and in both cases the effects were enhanced for colour relative to orientation cues. This indicates that the greater effects from colour cueing can arise from 'pure' top-down cueing[3].

3.5.1: Top-down colour segmentation

Both colour and orientation cues reduced the slopes of the search functions (Experiments 3.1 and 3.3). I have suggested that this reflects participants starting search with the cued group, whereas on neutral trials they select colour and

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[3] Prior studies, outlined in Chapter 2, had established colour and orientation-defined targets were equally salient, for all of the experiments subsequently presented.

orientation groups equally often. However, the advantage for colour over orientation cueing was additive with the effects of display size. I conclude that there was no difference between colour and orientation in terms of determining which group was searched first. Rather than this, I propose that colour cues facilitated the segmentation of the displays into colour groups more than orientation cues facilitated the segmentation of the displays into orientation groups. Thus, even though both forms of segmentation may operate in parallel (see above), colour cueing allowed colour segmentation to finish earlier in time, allowing search through the colour groups to be initiated earlier.

According to this account, colour cues exert a strong priming effect on colour segmentation (e.g., Hannus et al., 2006). This can operate even from verbal representations of the colour cues, so the ‘set’ for colour can be imposed from higher-level representations that are abstracted from perceptual representations of colour. Recently Soto and Humphreys (2007) have provided evidence that verbal information held in working memory can guide visual attention to a subsequent search display, even when the memory information is irrelevant to the search task. This is highly reminiscent of the verbal effects of the colour cues here, except that I am proposing that the effects of the colour cues are on an initial segmentation stage rather than guidance of search per se. One way to account for these cross-modal cueing effects is to suggest that information is held in working memory in a representation abstracted from the perceptual features of the stimulus, perhaps akin to the idea of an episodic buffer put forward by Baddeley (2000). This representation feeds back activation to earlier perceptual processes, enabling them to be completed more efficiently.

Our data indicate that any feedback from higher-level processes facilitates segmentation of displays by colour more than by orientation. However, I found in

Experiment 3.2 that bottom-up segmentation and guidance of search to the smaller of two orientation groups was more effective than the bottom-up segmentation and guidance of search to the smaller of two colour groups (in the neutral condition). The stronger top-down effect of colour, then, has to overcome the initial stronger bottom-up effects.

This dominance for colour segmentation has been found previously (see Williams, 1966; Hannus et al., 2006 and 1.5.4 for details). One proposal by Hannus et al. was that orientation and size discrimination suffer from "crowding", e.g., the detrimental influence on feature discriminability generated by the presence of surrounding objects. Colour discriminability, they proposed, is unaffected and they suggested that visual search theories should be amended to give colour a preferential role in guiding attention. This crowding explanation could easily be linked to our preferential colour segmentation proposal, with the ease of segmentation of stimuli differentiated by colour reducing the effects of adjacent stimuli on discrimination. Indeed, Mollon (1989) has previously suggested an evolution-driven advantage for colour vision, with colour-blind people finding it difficult to detect coloured fruit surrounded by foliage of varied luminosity. He suggests that colour vision facilitates the segregation of the visual field, offering advantages in identifying objects.

3.5.2: Theoretical models

What are the implications of these results for functional theories of visual search? Guided Search Theory (GST: Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) proposes that there is an initial preattentive parallel stage of visual processing where basic visual features are coded independently in distinct retinotopic 'feature maps'. Activation within the feature maps will reflect both the bottom-up saliency of the stimuli (e.g., generated by local differences between elements) and top-down cueing (pre-activation of the maps by foreknowledge of the target). Within this framework, pre-cueing in our studies should increase the activation of the stimuli sharing the cued feature, facilitating their selection over items not subject to top-down cueing. As a consequence, segmentation of the stimuli, and selection of one group of elements based on the cued feature, may be faster relative to when the cue is neutral. On a valid trial, search will be facilitated as the target will be a member of the selected group. This comes at the cost of performance on an invalid trial, when a distractor group will show speeded selection and attention may need to be disengaged in order for the target to be subsequently selected. This effect may emerge on the intercepts rather than the slopes of the search functions if search, even on neutral trials, is based on the segmentation into sub-groups of stimuli, but with this process occurring faster on trials where a feature cue is present.

Now, when the ratio of distractors is manipulated (Experiment 3.2), the smaller group of distractors will benefit due to these items having increased local differences relative to the other distractors (cf. Sobel & Cave, 2002). These differences between distractor ratios would be reflected in the GST salience map, with increased activation for stimuli in the smaller subset. In addition, the bottom-up modulations based on the distractor ratio should occur in parallel to those induced top-down by the cue. Our data indicate that, at least with the current displays, top-down modulation was stronger than the bottom-up effects so that robust effects of cueing occurred even when there were uneven ratios of the different types of distractor. This occurred even when the top-down cue directed attention to the larger distractor group (there remained a cost to performance). Nevertheless, the switching of attention to the invalidly cued group was easier when the distractor ratio was small, compared with when there was an equal ratio of distractor types (see Figure 3.5). This in turn suggests that the bottom-up salience of the smaller set of distractors was maintained, even if the cued set of distractors was selected first. On winner-take-all accounts of visual selection, there would be a loss of any increased bottom-up activation for the smaller distractor group on trials where the larger top-down group 'wins' the competition for selection. The present results indicate that, even when this happens, either activation differences favouring the smaller group are maintained in the feature maps, or processing continues to take place after any initial top-down biased selection, with the bottom-up cues again favouring the smaller distractor group.

Data consistent with the argument for early effects of top-down cueing comes from our analysis based on RT distributions in Experiment 3.4. Here I found a larger modulation of selection by colour than orientation at the fast as well as the slow end of the response distributions. The same pattern of effects were present whether the target was visual or verbal, indicating that the cueing effects on search did not reflect processes driven by the physical nature of the cue.

Although GST can account for the relationship between top-down and bottom-up guidance of attention, the model has little to say about our observed differences between the top-down cueing of colour and orientation. Wolfe (1994) suggested "that colour information guides attention more effectively than orientation" (page 208), without distinguishing between top-down and bottom-up guidance. Our results, however, indicate that there may be increased gain on the top-down input into the colour feature map, thereby increasing the top-down biases towards segmentation into a winning and losing group. This facilitated segmentation from colour cueing would generate an overall RT advantage even if there is subsequently serial selection within the ‘winning’ group of items.

It is of interest that while top-down cueing of colour appeared more effective than that of orientation, the data on bottom-up effects of distractor ratio generated the opposite picture. In Experiment 3.2, in the neutral, uncued condition search was fastest when the orientation of the smaller group of distractors matched that of the target. For trials with a green vertical target, RTs were shortest when there were three blue vertical distractors, both compared to when the ratio was balanced and when there were three green horizontal distractors. Likewise, for trials with a blue horizontal target search was fastest when there were three horizontal distractors. The smaller orientation-defined subset, therefore, guided attention more efficiently than a colour-defined subset of the same size. This contrast between the different dimensions, even when overall saliency was matched (see Chapter 2) provides strong evidence for the two forms of saliency (bottom-up and top-down) being ‘driven’ independently in search, even if their outputs are subsequently pooled in the competition for selection.

An alternate proposal is that search was initially directed to the smaller subset of stimuli grouped in colour. This group either has the same colour as the target (see Figure 3.3c) or matches it in orientation (see Figure 3.3a). As the latter colour group does not include the target, it may be more salient than a subset that does (Duncan & Humphreys, 1989). Following this initial advantage, search may then be quickly directed to the target by orientation-grouping processes (cf. Hodsoll & Humphreys, 2005). Therefore, rather than search being preferentially guided by an orientation-defined subset, it may be that search was directed by stimuli grouped by colour.

Further evidence, perhaps from eye movements during search, would be needed to substantiate this hypothesis.

A somewhat different account of the data can be formulated in terms of Attentional Engagement Theory (AET, Duncan & Humphreys, 1989, 1992). AET is a two-stage model in which there is preattentive grouping of stimuli followed by a matching of the representations to a template of the target. Pre-cueing the target will increase the ‘pertinence’ of matching distractors, enabling them to win the competition for selection (cf. Bundesen, 1990; Heinke & Humphreys, 2003; for similar, more formal accounts). For this account a distractor ratio effect may arise because spatial grouping between the larger set of distractors enables them to be rejected together, enabling the smaller set of distractors to be selected. Our data can be accounted for if the top-down cueing of the target’s template acts to off-set the rejection of the larger group of distractors, so that these items are selected first. The effect would emerge on the intercepts rather than the slopes of the search functions because of pre-attentive segmentation of stimuli into distractor groups, and the cueing effects simply reflect which group is selected first.

Whichever account of the data is maintained, the important result is that the top-down and bottom-up cueing effects appear to be functionally independent, and lead to opposite efficiencies for the different dimensions of orientation and colour.

3.5.3: Response-based accounts of performance

Our data counter the proposal by Theeuwes et al. (2006) that top-down effects on selection (in their case, from intra-trial cueing) influence response selection. Theeuwes et al. used a verbal cue that predicted which dimension defined the target of a following feature-singleton search. Effects of cue validity were present when there was a present-absent response decision, but not when the decision was irrelevant to the search (see also Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997 and 1.4.3 for details). However, contrary to Theeuwes et al*.,* I cued the feature of a conjunction target rather than the dimension of the stimulus in an efficient feature-based search task. In our present-absent task (Experiment 3.1), the response-decision was consistent regardless of the cue and required information from both dimensions – colour and orientation. This would likely reduce any direct link from the cued dimension to the response. Even stronger evidence comes from Experiment 3.3 here, where top-down cueing effects emerged in a compound search task, where the response was unrelated to the cued dimension. I conclude that the cueing effects here were not due to linkage of the cue to a response.

3.5.4: Hard vs. easy search

Previous investigators have assessed whether top-down effects influence easy or difficult conjunction search differently. In Sobel and Cave (2002), observers searched for a colour-orientation conjunction target amongst two sets of distractors of varying ratios (see our Experiment 3.2). When both dimensions were easily discriminable, participants preferentially searched the smaller subsets of distractors, irrespective of whether the subsets were defined by colour or orientation. Also, as the discrimination of the orientation dimension was more difficult, so participants were more likely to search the colour subset for the target. This shows that there is a balance between top-down and bottom-up cues for selection, with bottom-up cues emerging more strongly when there was differential discriminability along the dimensions of the stimuli. Indeed in Experiment 3.2 here, bottom-up saliency effects seem less effective than top-down cues for selection. Heinke, Humphreys and Tweed

(2006) compared the effect of pre-cueing of the target on easy – a V surrounded by rotated Ls – and hard – an upright L surrounded by rotated Ls. They found stronger cueing effects when the search was easy compared with when it was more difficult and suggested that the target needed to have a sufficient level of discriminability in order to make contact with any (pre-activated) template for the target. The studies outlined in Chapter 2 showed that the target properties were relatively salient along each dimension (colour and orientation), and this may have been helpful in order to allow the top-down effects to emerge.

In addition to this, I showed that the top-down cueing effects were equally strong from written as from visual representations of the target. It is possible that participants were able to translate the written cue into a visual image, and this acted in place of a visual template, guiding search. Alternatively, participants may extract semantic information from the visual displays which can be rapidly mapped onto a verbal representation for the target (see Soto & Humphreys, 2007). In either case, the data show that top-down cueing does not depend on a physical representation of the target being present (cf. Wolfe et al., 2004).

3.5.5: Conclusion

I conclude that there can be differential top-down cueing of attention based on the expected colour rather than the orientation of a target, even under circumstances in which bottom-up segmentation based on orientation seems strong. This effect occurs with words as well as visual representations of stimuli and it occurs in compound as well as present-absent search tasks. That stronger guidance following colour cues occurs in conjunction with a stimulus-driven bias towards orientation points to there being independent ‘drivers’ of top-down and bottom-up cueing in search.

CHAPTER 4

Differential Time Course of Predictive and Non-predictive Effects from Colour and Orientation Cues in Visual Search

Chapter 4 is similar to Anderson, G., M., Heinke., D., and Humphreys, G., W. (under review). Differential time course of implicit and explicit cueing by colour and orientation in visual search. *Visual Cognition. Under review.*

4.0.1: Abstract

Three experiments examine predictive and non-predictive effects of visual cues on visual search. In Experiment 4.1, cues were both predictive and matched the physical properties of the target on 80% of the trials. For cue durations ranging from 100ms to 1200ms there was a greater facilitation effect from valid cueing of the target's colour than cueing its orientation. On invalid trials, there was a stronger cost from colour cues only when cues were presented for 200ms. Experiment 4.2 introduced a non-predictive feature to the cue that randomly matched the colour or orientation of the target. When the orientation of the cue was predictive, there were strong non-predictive effects based on whether the colour of the cue matched that of the target; in contrast, when the colour of the cue was predictive there were only weak effects of whether the cue matched the target's orientation. To test the automaticity of these non-predictive effects, orientation-predictive cues were used whose colour was systematically opposite to that of the target (Experiment 4.3). The non-predictive effect from colour-matching between the cue and target remained, though it was reduced relative to when the colour had a higher probability of matching the target. The data suggest that automatic priming from visual cues can play a substantial role in guiding search, particular when based on the cue's colour.

4.0.2: Introduction

The process of selecting relevant visual information has been traditionally investigated by measuring the time taken (reaction times or RTs) to find a specific target amongst distractor items, with the identity of this target the same across a block of trials (see Wolfe, 1998, for a review). Participants learned about what they were looking for (the target template) either from explicit instruction or during practice trials. More recently, researchers have investigated how the development of this template is set up by changing the target identity trial-on-trial while presenting information about the target prior to the search task (e.g., pre-cueing; Anderson Heinke, & Humphreys, 2010[4]; Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006; Moores, Laiti & Chelazzi, 2003; Müller, Reimann, & Krummenacher, 2003; Theeuwes, Reimann, & Mortier, 2006; Vickery, King, & Jian, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004).

Both verbal and visual cues have been shown to affect search behaviour. Wolfe et al. compared RTs in a conjunction search when a visual representation of the target (e.g., a red vertical stimulus) was presented prior to each trial with performance when verbal cues were preceded each search (e.g., the words 'RED VERTICAL'). Search speeds were facilitated following either type of cue compared to when no information about the target was available, indicating that both physical and abstract information can be used to set a template of the search target. However, there was larger facilitation from visual cues which reached a maximum after only a short time (a stimulus onset asynchrony, or SOA, of 200ms), before having a decreasing effect on search efficiency at longer SOAs. Guidance from verbal cues took longer and still had an increasing effect at longer SOAs, although the effects did not match those of visual cues, even at the 800ms SOA. Wolfe et al. suggested the advantage of visual representations was due to 'implicit top-down guidance', with the physical nature of the cue enhancing the guidance towards the target. Vickery et al. (2005) also demonstrated an advantage for visual vs. verbal cues. Using searches based on abstract and real-world items, they found the efficacy of the cue was dependent on its similarity to the target image. While there was maximum facilitation for search RTs

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[4] See Chapter 3.

when the cueing image exactly matched the target, this benefit was reduced when the cue differed in size or orientation and further decreased when the cueing information was presented in word form (e.g., verbal cues). Vickery et al. suggested that the added facilitation from exact visual cues was a consequence of the efficient setting up of the target template being reliant on having a detailed visual representation held in working memory. The added facilitation from exact vs. non-exact visual cues, however, decreased following a longer cue leading time (1000ms) leading the researchers to propose the reduction to be due to the visual information being forgotten.

It is at present unclear, however, whether effects on search behaviour following visual cues are due to explicit processing of the cued information or due to priming from its physical nature not under top-down control. Several studies have shown 'inadvertent' effects on the deployment of attention from verbal cues (Huettig & Altman, 2005; Moores et al., 2003; see 1.5.4.5 for details). Their findings indicate that the physical properties associated with the cue as well as predictive cue information affects the setting up of the target template, guiding attention towards items that are inadvertently linked to the target attributes.

It is not just higher-level concepts associated with the cue that affect search behaviour. Both predictive and non-predictive effects from visual features of a stimulus in working memory have been shown to influence RTs, with stronger effects from stimulus colour versus orientation/shape (see 1.5.4.5). Advantages for search following predictive colour over other types of visual cue have also been reported by Anderson et al. (2010), as outlined in Chapter 3.

The above series of studies indicate that both the physical nature and predictive information associated with cues can affect search. This suggests that both types of processing could be active following visual predictive cues. In Anderson et al. (2010), then, either type of cueing could be responsible for the stronger guidance following colour compared to orientation cues. In the current set of studies, I set out to separate the effects of physical and predictive processes following visual cues. To avoid bias in the ease of search for colour- or orientation-defined targets, prior studies were undertaken in which the colour levels of the stimuli were adjusted until search performance was matched across the two dimensions (cf. Bacon & Egeth, 1997; see Experiment 2.3 for details). I then set up a baseline measure in which the stimulus-driven and predictive information about the target were the same, replicating the methodology of Anderson et al. while varying the duration of a visual cue (Experiment 4.1). Search was for either a blue horizontal or green vertical bar amongst blue vertical and green horizontal distractors. A pre-cue either predicted the colour or orientation of the target with colour cues in the form of circular coloured patches and orientation cues presented as white oriented lines. The featural information of the cue was valid on 80% of the trials and invalid on 20% (see Müller et al., 2003). Subsequently, I added a non-predictive feature to the cue which enabled me to measure if the predictive effects of the cue were affected by an unrelated physical property matching or differing from the target. In Experiment 4.2, cues were lines whose colour and orientation were predictive (80% validity) in separate sessions, while the corresponding feature (e.g., the orientation of a colour line cue) matched that of the target on 50% of trials.

To provide a stronger test of automaticity of any priming effects from the non-predictive cue feature, I then pitted the effects from the physical nature of the cue against its predictive properties. Experiment 4.3, therefore, investigated whether effects of the non-predictive colour of the cue affected search when the likelihood of the cue-colour matching the target was below chance. Cue orientation was predictive (as previously at 80% validity) while the colour of the cue matched the target only on 20% of trials. Any resultant effects of cue colour could therefore be attributed to priming from the physical nature of the visual cues used.

Experiment 4.1: Predictive Cueing Following Varying Cue Durations

4.1.0: *Introduction*

Previous research has shown larger modulation of search behaviour following cues predicting the colour of the target compared to when information about its orientation was cued (Anderson et al., 2010; Müller et al., 2003). However, the predictive information available following visual cues can be viewed as both explicitly represented (e.g., with a template used to guide search to a target; Duncan & Humphreys, 1989) and represented by the physical property of the cue matching the target, even if that property was not used to predict the target. Guidance from top-down processes has been shown to be slower to develop in comparison to stimulus-driven effects (e.g., Wolfe et al., 2004). In Experiment 4.1, the duration of a predictive visual cue to the colour or orientation information of the target was varied. The search involved two targets, blue horizontal and green vertical bars, and two types of distractor, blue vertical and green horizontal (a 50:50 ratio for each distractor type). A pre-trial stimulus cue predicted either the colour (a green or blue patch) or orientation (horizontal or vertical white line) of the target at 80% validity (cf. Müller et al., 2003). The presentation of the cue was varied between 100ms and 200ms (Experiment 4.1.2) and between 200ms and 1200ms (Experiment 4.1.3). Stimulus-driven dimensional differences should be evident at shorter durations, while variation following longer cues should reflect top-down guidance from the cue.

Experiment 4.1.1: 100-200ms cue duration

4.1.1.1: Method

The methodology matched that of the conjunction search used in Experiment 2.3 with the following exceptions.

Participants. Eighteen University of Birmingham students, five male, 13 female, aged 18-28 (average 21.95) took part in the experiment.

Design. This was a within-participant design, with four independent variables: cue validity (valid, neutral, invalid), cue duration (100ms, 200ms), cued dimension (colour, orientation) and target type (blue horizontal, green vertical).

Stimuli. The pre-trial fixation stimulus was a white circle, 0.6cm in diameter (visual angle of 0.57º), line width of 0.1cm (0.095º). The stimulus presented prior to each cued trial was one of four stimuli: a blue patch, a green patch, a white horizontal bar or a white vertical bar. The patches were colour cues in the shape of filled circles, all with the diameter of 0.35cm (0.34º), coloured to match the stimuli in the search array (green or blue). The physical dimensions of orientation cues (vertical or horizontal) were also the same as the search stimuli, although the cue stimuli were white. All stimuli were presented on a black background, with the search array comprising blue vertical or green horizontal bars as distractors and either a blue horizontal or green vertical bar as the target. Exploratory experiments were undertaken so that the target-distractor saliency within each dimension was balanced (see Experiment 2.3 and Table 2.1 for details).

Procedure. Participants took part in a one-hour session, undertaking both a neutral block of trials without cues (60 trials) and two blocks of cued trials (each block had 120 trials), with block order counterbalanced. The neutral block was preceded by 10 practice trials where RTs and accuracy was not recorded; prior to the cued blocks there were 15 practice trials.

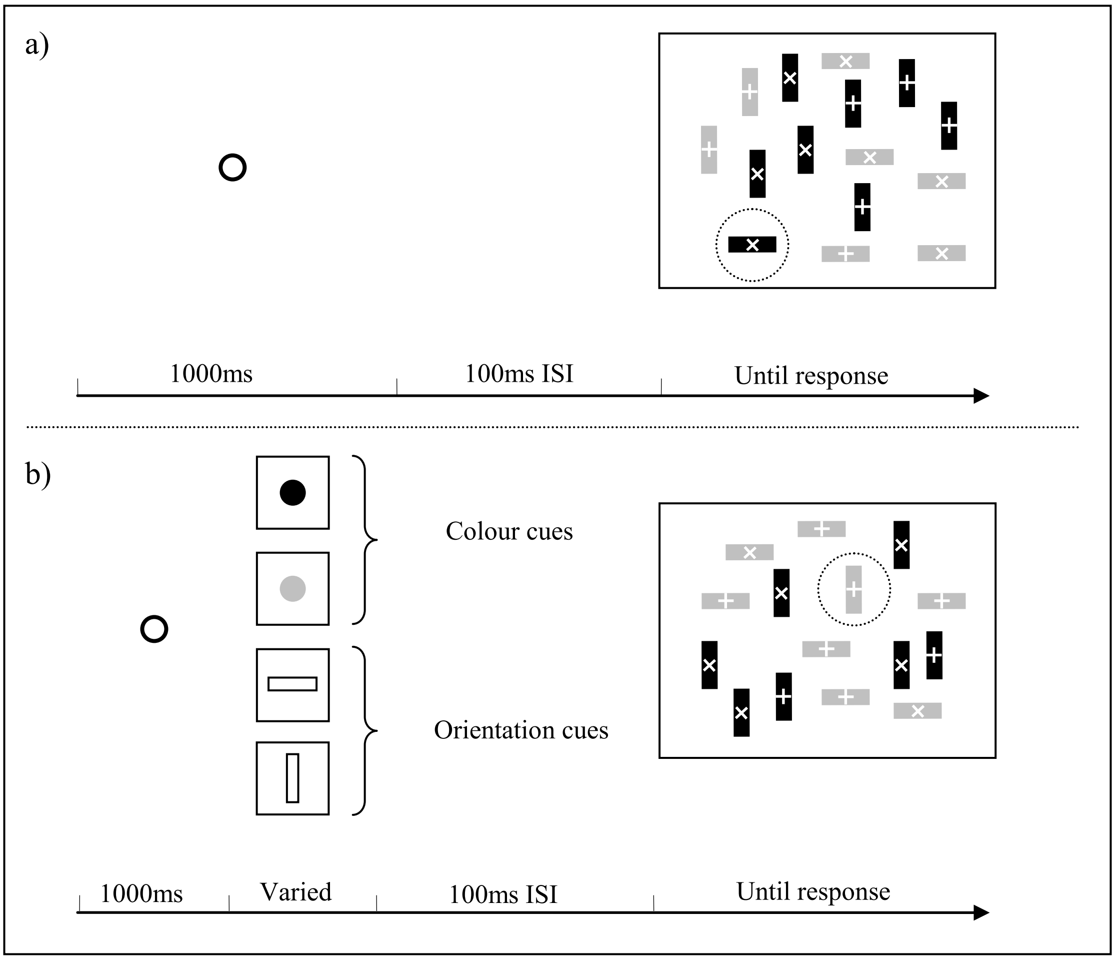

Figure 4.1. Simplified trial timelines for Experiment 4.1. Fig. 4.1a outlines the neutral trial methodology while Fig. 4.1b outlines the timeline of a cued trial. Blue stimuli are shown as black, green as grey, white as outline, black background and light grey symbols as white. A blue horizontal target is circled in Fig. 4.1a and a green vertical one in Fig. 4.1b, although either could be present on each neutral or cued trial.

On neutral trials, a fixation circle was present for 1000ms. This was followed by a 100ms inter-stimulus interval (ISI) before an array of stimuli with one target and 14 distractors. Cued trials matched those in the neutral condition, except a cue was presented for either 100ms or 200ms between the fixation cross and the ISI prior to the onset of the search array. On half the trials the cue predicted the colour of the target (colour cues, 80% valid), on half it predicted the target's orientation (orientation cues, 80% valid). A green or blue patch was used as a colour cue, and a white vertical or horizontal line formed the orientation cue with the nature of the cue randomized trial-on-trial. The nature of the cues varied randomly across trials. As well as the possible target configuration, participants were informed prior to the cued blocks that the majority of the cues were valid. Trials with the same presentation time were blocked, with block order counterbalanced across participants.

4.1.1.2: Results

RT Cost-Benefits. The data were cleaned as in Chapters 2 and 3. As previously, the neutral condition was used as baseline with the effects of cueing calculated for each participant by subtracting median RTs from cue trials from median RTs on corresponding neutral trials. The effect of the predictive feature being valid was reflected in positive RT Benefits; while RT Costs indicated the effect of the predictive feature being invalid. Group means are shown in Figure 4.2.

A three-factor ANOVA (cue duration, cue dimension, cue validity) found a main effect of validity ($F(1,17)=103.8$, $p<0.001$, partial $\eta^2=0.859$) and interactions between cue dimension and cue validity ($F(1,17)=16.8$, $p=0.001$, partial $\eta^2=0.497$) and cue duration and cue validity ($F(1,17)=5$, $p=0.039$, partial $\eta^2=0.227$). The three-way interaction failed to reach significance ($F(1,17)=1.5$, $p=0.245$, partial $\eta^2=0.079$). Separate analyses of RT Benefits and RT Costs were undertaken (relative to the neutral condition). Analysis of RT Benefits from valid cueing showed a main effect of cue dimension ($F(1,17)=42.8$, $p<0.001$, partial $\eta^2=0.716$). There was a larger effect of colour cues (an effect of 811ms) compare to orientation cueing (an effect of 489ms), with this advantage for cue colour matched across cue durations (cue duration x cue dimension: F<1). RT Cost data showed no main effects or interactions (all ps>0.2).

Accuracy. Error rates followed the pattern of reaction times with no speed-accuracy trade-off evident. Mean accuracy is presented in Table 4.1.

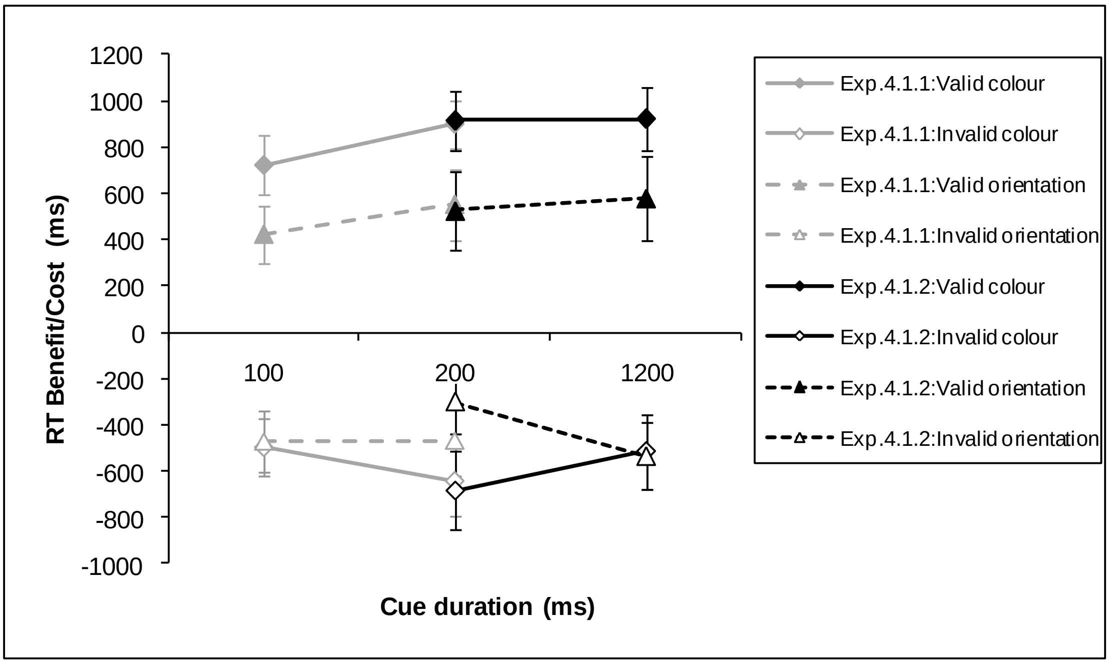

Figure 4.2. Mean RT Benefits/Costs (+/- standard error) from Experiment 4.1, separated by cue duration, cue dimension and cue validity. Data from Experiment 4.1.1 are shown in grey; Experiment 4.1.2 data are shown in black.

Experiment 4.1.2: 200-1200ms cue duration

4.1.2.1: Method

The methodology for Experiment 4.1.2 matched that of Experiment 4.1.1 except that the cue duration was varied from 200ms to 1200ms. Specific differences are outlined below.

Participants. Eighteen University of Birmingham students, five male, 13 female, aged 18-25 (average 19.83) took part.

Procedure. Neutral blocks were as Experiment 4.1.1. However, in cued blocks cues were presented for either 100ms or 200ms.

4.1.2.2: Results

RT Cost-Benefits. The data were cleaned as in Experiment 4.1.1. Benefits from valid cues and costs from invalid cues were calculated as previously, however only the effects of cueing are reported (the neutral condition was used merely as a baseline). Group means are shown in Figure 4.2.

A three-factor ANOVA found main effects of cue dimension (F(1,17)=5, p=0.038, partial η^2=0.229) and cue validity (F(1,17)=157.3, p<0.001, partial η^2=0.902). Two two-way interactions were evident: cue duration x cue dimension (F(1,17)=4.8, p=0.044, partial η^2=0.219) and cue dimension x cue validity (F(1,17)=10.8, p=0.004, partial η^2=0.389), as well as a three-way interaction (F(1,17)=6.3, p=0.022, partial η^2=0.271). To unpack the three-way interaction, the effects of valid cues (RT Benefits) were analysed separately to the effects of invalid cues (RT Costs). Analysis of RT Benefits showed only a main effect of cue dimension (F(1,17)=21.3, p<0.001, partial η^2=0.556), reflecting a larger benefit from valid colour cues (an effect of 919ms) compared to orientation cues (an effect of 553ms). Analysis of RT Costs revealed a cue duration x cue dimension interaction (F(1,17)=6.1, p=0.024, partial η^2=0.264) with a larger cost from invalid colour cues at the shorter cue duration (a difference of 382ms, p=0.018) but no corresponding difference at the longer cue duration (a difference of 21ms, p=0.858). No other main effects or interactions reached significance.

Experiment	**Cue type**	**Cue duration (ms)**		
		100	200	1200
4.1.1	Valid colour cueing	95	95	
	Valid orientation cueing	96	96	
	Neutral, uncued	94		
	Invalid colour cueing	95	93	
	Invalid colour cueing	95	95	
4.1.2	Valid colour cueing		95	97
	Valid orientation cueing		96	95
	Neutral, uncued	98		
	Invalid colour cueing		97	93
	Invalid colour cueing		97	95
4.2	Valid colour, orientation matches	97	98	
	Valid colour, orientation differs	97	96	
	Invalid colour, orientation matches	98	96	
	Invalid colour, orientation differs	98	97	
	Neutral, uncued	96		
	Valid orientation, colour matches	97	98	
	Valid orientation, colour differs	97	97	
	Invalid orientation, colour matches	97	97	
	Invalid orientation, colour differs	96	96	
4.3	Neutral, uncued	97		
	Valid orientation, colour matches	96		97
	Valid orientation, colour differs	97		96
	Invalid orientation, colour matches	98		98
	Invalid orientation, colour mismatch	97		96

Table 4.1. Mean accuracy (%) for all experiments in Chapter 4.

Accuracy. Error rates followed the pattern of RTs with no evidence of a speed-accuracy trade-off. Mean accuracy is presented in Table 4.1.

4.1.3: Discussion

As in Anderson et al. (2010), there was a strong modulation of attention when both the physical and predictive properties of a visual cue either matched (valid cues) or differed (invalid cues) to the target of the following search. Relative to an uncued condition, valid cues facilitated search (a benefit) while invalid cues led to longer RTs (a cost). There was a larger benefit when the colour of the cue matched that of the target compared to valid orientation cueing, although differences between the effects of colour and orientation cues were reduced when the cues were invalid. A larger cost from invalid colour cues was evident when the cue was presented for 200ms, but this effect was reduced for shorter and longer cue durations (e.g., 100ms and 1200ms, respectively). The stronger benefit from valid colour cues, however, was robust across cue durations.

Presenting information prior to a search task has been shown to guide attention towards stimuli with features matching the cued information, whether this link is predictive (Anderson et al, 2010; Hannus et al., 2006; Williams & Reingold, 2001; Williams, 1966) or not (Becker & Horstmann, 2009). In the current study valid cueing may facilitate search by directing attention to the target subset, enabling it to be detected faster than when no cue is present (cf. Bacon and Egeth, 1997; Egeth, Virzi, & Garbart, 1984). The stronger benefit following valid colour cues is consistent with previous research (e.g., Hannus et al, 2006; Kristjánsson, 2006; McBride et al., 2007; Soto & Humphreys, 2009). The colour advantage was robust even at short durations, suggesting an early difference in processing the colour and orientation information.

Moutoussis and Zeki (1997) have previously shown differences in the speed of perceiving colour and orientation. They presented a coloured checkerboard on one half of a display and grey bars on the other half. The colour of the squares on the checkerboard switched between green and red (the remaining squares were black) while the orientation of the bars varied between being right- or left-tilted. Participants indicated the colour of the checkerboard squares when the bars were titled to the right or the left. The speed with which the colour and orientation of the two half-displays oscillated was the same, however the phase relationship was varied. The methodology therefore allowed differences in the speed of perception to be measured with the findings indicating that colour was perceived before orientation by 63ms. The stronger guidance following colour cues in Experiment 3.1 can therefore be seen as a consequence of earlier detection of the colour information possessed by the cue, offering an advantage to search compared to when orientation information about the target is cued.

Behaviour following invalid cues may closely match that following valid cueing, except that in this case search is guided to stimuli matching the cue in colour or orientation. Since the cued subset does not contain the target, attention may need to be disengaged from its current focus and re-oriented towards uncued stimuli for the target to be detected (cf. Kean & Lambert, 2003). Since attentional disengagement takes time, there is a cost to search speed relative to the neutral condition. If the same process is involved on valid and invalid cue trials, then I would expect a stronger effect again with colour cues, relative to orientation cues. However, a difference in performance after colour and orientation cues was not evident. Anderson et al. (2010) previously demonstrated a larger cost following invalid colour cues, compared to invalid orientation cueing. They proposed there was a disengagement cost to re-orienting attention away from the cued stimuli in a colour-defined rather than an orientation-defined group (cf. Kim & Cave, 1999). This cost offsets any early benefit in guidance from colour cues. In the current study, however, the disparity in the effect of invalid colour and orientation varied depending on the cue duration, with a larger cost evident from colour cues only following 200ms cues. This variation across cue durations could demonstrate differences in the effects from the physical and predictive properties of the cue on search when the cue is invalid. At shorter cue durations (e.g., 100ms) there may be insufficient time for the development of the predictive colour information associated with the cue (cf. Wolfe et al., 2004). This would result in a reduction in the larger disengagement cost following invalid colour cues (e.g., when the cue was presented for 200ms). The diminishing in this larger cost following longer cues (1200ms) may be due to the degrading of larger priming effects from the colour of the cue over time (Vickery et al., 2005; Wolfe et al., 2004), with this decrease only evident during the longer RTs of invalid trials. The effects of cue duration may be more evident on costs than benefits if the colour cue affects attentional disengagement (on invalid trials) over and above effects on initial attentional guidance (on valid trials). Effects on attentional disengagement may be maximised with a 200ms colour cue.

The results of Experiment 4.1, therefore, could be interpreted as reflecting an early stimulus-driven advantage for colour cueing, with the coding of orientation occurring later and perhaps involving the slower processing of non-visual concepts associated with cue information (cf. Wolfe et al., 2004). However, effects from the predictive and the physical properties of the cue cannot be separated in Experiment 4.1. In Experiment 4.2, I introduced cues where one feature had a predictive link with the target while the secondary feature either matched or differed from the target at chance. While the effects from the predictive information could be due to both top-down and stimulus-driven effects, any modulation from the relationship between the non-predictive feature and the target would offer a measure of stimulus-driven processes occurring following the cue.

Experiment 4.2: Non-predictive Cue Features

4.2.1: Introduction

The modulation of RTs following visual cues could be due to the physical nature of the cue, without the engagement of processing under the control of the visual system's user (top-down mechanisms). Search would therefore be guided to search stimuli matching the cue colour/orientation in a reflexive manner (cf. Posner et al., 1982). Indeed, recent research has revealed that eye movements are biased towards fixating stimuli sharing a feature with the target on the previous trial (Becker & Horstmann, 2009). The stronger modulation from colour cues demonstrated in Experiment 4.1 may be due to differences in priming, rather than an asymmetry in the processing of the predictive information of the cue. In Experiment 4.2, therefore, I introduced cues where both a predictive feature and a non-predictive feature were present with participants asked to ignore the latter cue feature. Coloured lines were used so that in one session the cue colour was predictive (80% valid) while its orientation matched[5] the target 50% of the time. In a separate session, cue orientation was predictive (80% valid) and its colour matched the target at 50%. Any effect of the non-predictive feature would therefore offer a measure of priming processes. Cue

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[5] I differentiate between cue validity, where there is a predictive link between cue feature and the target, and whether the cue matches or differs to the target where any link was non-predictive.

duration was again varied to assess differences in the timeline between predictive and non-predictive effects.

4.2.2: Method

The methodology for Experiment 4.2 followed that of Experiment 4.1.1 except as outlined below.

Participants. Eighteen University of Birmingham students, three male, 15 female, aged 18-29 (average 22.2) took part.

Design. There were five independent variables: dimension of predictive feature of the cue (colour, orientation), validity of predictive feature of the cue (valid, invalid), non-predictive feature status (whether it matches or differs from the target), cue duration (100ms, 200ms) and target type (blue horizontal, green vertical).

Stimuli. The cueing stimuli used were blue horizontal, green vertical, blue vertical or green horizontal bars. The colour and spatial dimensions of the cues matched those of the stimuli used in the search array, but without the response-defining symbols.

Procedure. Participants took part in two one-hour sessions, with a minimum of 24 hours apart. In each session, participants undertook 60 neutral trials, identical to those used in Experiment 4.1, and two blocks of 120 cued trials, with cues presented for 100ms in one block and 200ms in the other. Block order was counterbalanced across participants. Before the neutral blocks there were 10 practice trials, where RTs and accuracy were not recorded; there were 15 practice trials before the first of the cued blocks.

The cueing stimulus on each trial could be either a blue horizontal, green vertical, green horizontal or blue vertical bar. In one experimental session, the colour of the cue was predictive so that it was the same as the target 80% of the time and differed 20% of the time (cf. Müller et al., 2003) while orientation of the cue (the non-predictive feature) matched the target at chance (50%). The opposite was true in the other session (orientation predictive at 80%/20%, cue colour non-predictive) with session order counterbalanced across participants. The predictive feature of the cue could be either valid or invalid while concurrently the non-predictive feature would match or differ from that of the target (50% match, 50% mismatch). For each session, participants were informed of the predictive nature of the relevant cue feature and asked to ignore the non-predictive feature.

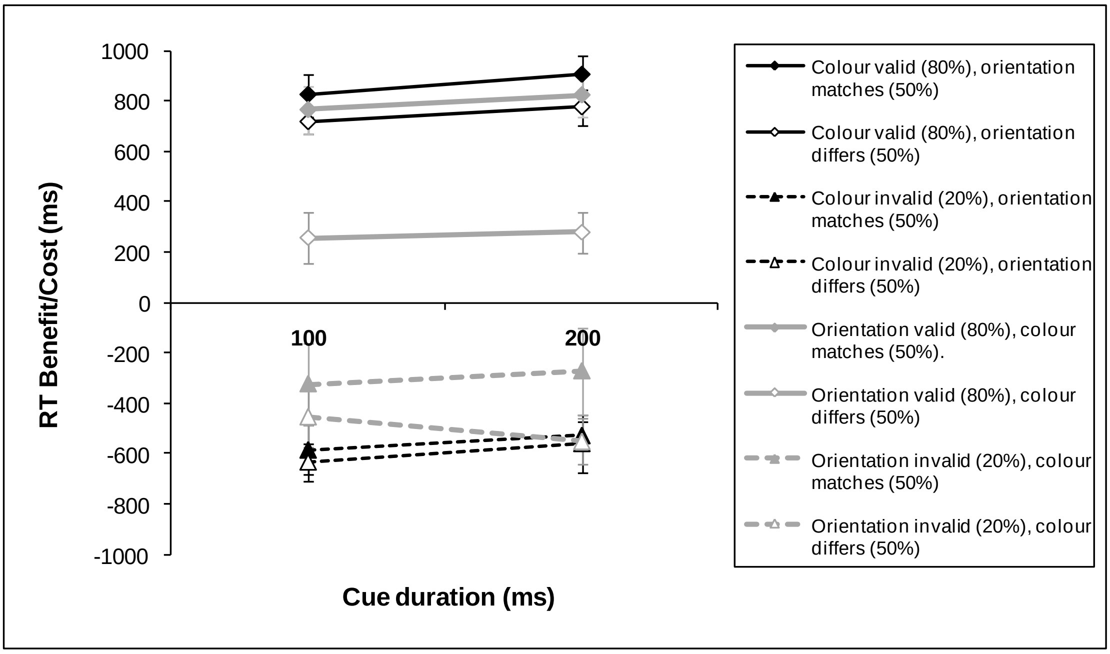

Figure 4.3. Mean RT Benefits/Costs (+/- one standard error) from Experiment 4.2, separated by predictive dimension, validity of predictive cue feature (valid or invalid), non-predictive feature status (whether it matches or differs from the target) and cue duration.

4.2.3: Results

RT Cost-Benefits. The data were cleaned as in Experiment 4.1. As previously, the neutral condition was used as baseline with the effects of cueing calculated for each participant by subtracting median RTs from cue trials from median RTs on corresponding neutral trials. Group means shown in Figure 4.3.

A four-factor ANOVA (cue duration, predictive cue dimension, predictive feature validity, non-predictive feature status) found a main effect of predictive feature validity (F(1,17)=181.8, $p<0.001$, partial $\eta^2=0.914$), with a benefit following valid cues (an effect of 667ms) and a cost following cues that were invalid (an effect of -489ms). There was also a main effect of the non-predictive feature status (F(1,17)=21, $p<0.001$, partial $\eta^2=0.553$), with a facilitation effect when the feature matched the target (200ms) and a cost when they differed (-22ms). There were several significant interactions: cue dimension x predictive feature validity (F(1,17)=13.8, $p=0.002$, partial $\eta^2=0.447$), predictive cue dimension x non-predictive feature status (F(1,17)=6.9, $p=0.017$, partial $\eta^2=0.29$), predictive cue validity x non-predictive feature status (F(1,17)=7.3, $p=0.015$, partial $\eta^2=0.3$); and predictive cue dimension x predictive feature validity x non-predictive feature status (F(1,17)=5.9, $p=0.027$, partial $\eta^2=0.027$).

The data were decomposed by predictive cue dimension. The colour-predictive data reflected a robust main effect of predictive cue validity (F(1,17)=327, $p<0.001$, partial $\eta^2=0.951$), with valid cueing facilitating search (a benefit of 805ms) and invalid cueing slowing search (a cost of -579ms). There was also a borderline significant effect of the status of the non-predictive feature (e.g., orientation; F(1,17)=4.1, $p=0.059$, partial $\eta^2=0.194$), with a larger benefit when cue orientation matched the target (an effect of 153ms) compared to when there was a mismatch (an effect of 73ms). No other main effects or interactions reached significance ($p>0.2$).

Analysis of orientation-predictive trials found robust main effects of both predictive feature validity (F(1,17)=53.1, $p<0.001$, partial $\eta^2=0.758$) and the status of the non-predictive feature (F(1,17)=14.9, p=0.001, partial η^2=0.465). There was also a predictive feature validity x non-predictive feature status interaction (F(1,17)=10.5, p=0.005, partial η^2=0.381). When the predictive feature (orientation) was valid, there was a large benefit when the non-predictive feature (colour) of the cue also matched that of the target compared to when it differed (a difference of 528ms, p<0.001). When the orientation of the cue was invalid, however there was a sizeable effect of the non-predictive cue colour but this did not reach significance (colours matches vs. differs from the target, a difference of 203ms, p=0.131).

To directly compare the effects when cue colour and cue orientation were predictive, RT Benefits and RT Costs were analysed separately. The analysis of RT Benefits from valid cues showed main effects of predictive cue dimension (F(1,17)=21.4, p<0.001, partial η^2=0.557) and status of the non-predictive feature (F(1,17)=42.1, p<0.001, partial η^2=0.713). There was also a predictive cue dimension x non-predictive feature status interaction (F(1,17)=21.8, p<0.001, partial η^2=0.562). There was a larger benefit from cues when their colour was valid and its (non-predictive) orientation did not match the target's (e.g., a green horizontal cue followed by a green vertical target) compared to when its orientation was valid and cue colour differed from the target (e.g., a blue vertical cue followed by a green vertical target; a difference of 480ms, p<0.001). However, there was no difference between the effects of colour- and orientation-predictive cues when the non-predictive features matched the target (e.g., both features matched the target; a difference of 60ms, p=0.344).

Analysis of the RT Costs from invalid cues showed a borderline main effect of non-predictive feature status (F(1,17)=3, p=0.1, partial η^2=0.151) reflecting a trend towards a larger cost when the feature did not match the target (an effect of -551ms) compared to when it matched (an effect of -428ms). No other significant main effects or interactions reached significance (all ps>0.1).

Accuracy. No speed-accuracy trade-off was evident. Mean accuracy is presented in Table 4.1.

4.2.4: Discussion

The results demonstrate robust differences between the non-predictive effects of the colour and orientation of the cue, which were additive across cue durations. When the orientation of the cue was predictive, the cueing effect was influenced greatly by whether the non-predictive colour matched the target or not. Search was facilitated when cue colour was the same as the target compared to when the cue and target differed in colour, with this effect larger when orientation was also valid compared to when it was invalid (528ms vs. 200ms). In contrast, the effect of non-predictive orientation was smaller (80ms). The findings suggest that the colour of the cue was processed early (there was no variation with cue duration) and these processes occurred regardless of whether there was any predictive benefit, suggesting priming mechanisms from the physical nature of the cueing stimulus were involved (e.g., Soto & Humphreys, 2009). Indeed, when both cue features matched the target, there were similar effects of cueing whether colour or orientation was the predictive dimension (i.e., there was no difference between colour- and orientation-predictive cues), suggesting that the colour of the cue has a similar effect regardless of whether its relationship with the search target is predictive or not. Although robust non-predictive effects were evident, particularly of cue colour, I cannot conclude that the effects were purely stimulus-driven. For this to be the case, I would expect the effects to be automatic to the extent that participants were unable to inhibit the effects on search RTs (cf. Posner et al., 1982). In the present case, participants could still be attending to the colour information, even though instructed not to do this. The colour only matched that of the target at chance, so any effects of the strategic processing of cue colour would not be differentiated from priming effects. Participants could learn that while attending the cue colour was not beneficial to finding the target, there was no incentive to ignore the non-predictive feature if possible.

To provide a stronger test of automatic effects, in Experiment 4.3 I tested the priming effect of the colour cues while including a cost to attending to this feature (cf. Kean & Lambert, 2003). The orientation of the cue was predictive at 80% as previously (see Experiments 4.1 and 4.2), however the colour of the cue was contra-predictive, only matching that of the target on 20% of trials. Attending to cue colour would therefore be detrimental to performance (e.g., Soto et al., 2005). Cues were either short (100ms) or long (1200ms). I would expect automatic effects of cue colour to be evident at shorter cue durations, with search reflexively guided to stimuli sharing the colour of the cue. However, any explicit processing of the colour of the cue should be apparent following longer cues (cf. Posner et al., 1982). If the contra-predictive feature is processed in an top-down manner using it to guide search, the time between cue presentation and search would allow participants to override the effects of cue colour once they had become aware of the cost associated with the cue colour and alter their expectations accordingly (cf. Neely, 1997). Therefore, explicit processing of the cue colour would be demonstrated by either a reduction in its effects on search or, as participants realise the contra-predictive nature of cue colour, a switching of the effect of cue colour such that participants search for a target matching the opposite colour to that of the cue. There would therefore be a benefit when the colour of the cue did not match the target compared to when it did (cf. Posner et al., 1982).

Experiment 4.3: Contra-predictive Cue Colour

4.3.1: Introduction

From the data in Experiment 4.2 it was clear that presenting a visual cueing stimulus that matches or differs to the colour or orientation of the following target affected search behaviour. While modulation was evident when there was a predictive link between the cue feature and the target, there was also a strong effect when there was no predictive benefit from attending to the feature (e.g., it matched the target on only half the trials) and participants were instructed not to attend to it.

However, it is unclear whether these effects occur automatically following a visual cue. In Experiment 4.3, therefore, a cost to search behaviour was associated with attending to the non-predictive feature of the cue. As there were larger effects from the colour of the cue when it was not predictive, I focussed on the effects from cues with orientation predictive (and colour non-predictive). However, instead of the cue colour matching the target at chance (Experiment 4.2), the cue and target only possessed the same colour on 20% of trials while cue orientation was predictive as previously (80% validity). For the processing of cue colour to be automatic, the feature should affect search regardless of its relationship to the target (cf. Soto et al., 2005). Cue durations were either short (100ms) or long (1200ms). Automatic, stimulus-driven processing of the cue colour should be evident following shorter cues while a longer duration should allow the time for top-down processing of colour to affect behaviour (cf. Posner et al., 1982). If the effects of cue colour were not automatic, participants should be able to inhibit the effects of cue colour or even generate a reverse probability relationship and use it to increase the effect the cue (e.g., realise a blue cue is more likely to be followed by a green stimulus and direct attention accordingly). For example, in a semantic priming task, Neely (1997) showed that participants could alter their expectations so that responses to a word in a different category to that indicated by a prime was faster. On a trial, a word associated with buildings (e.g., 'door') was more likely following a 'body' prime, leading to facilitation in the categorisation of the word 'door' (whether it was a word or non-word). However, the effect of these type of primes was only evident at longer SOAs (e.g., 2000ms vs. 250ms) indicating participants require time to alter their expectancy.

4.3.2: Method

Experiment 4.3 replicated Experiment 4.2 except for the details outlined below.

Participants. Twenty-one female University of Birmingham students aged 18-37 (average 21.95) took part. One participant was removed due to accuracy of less than 90%.

Procedure. The neutral condition mirrored that of previous experiments. Cued trials were the same as those in Experiment 4.2 when orientation was the predictive dimension, with certain alterations. Cue duration was either 100ms or 1200ms and the probability of the non-predictive colour of the cue matching the target was changed from 50% to 20%. Therefore, while the predictive information from the orientation of the cue was 80% correct, the colour of the cue was only the same as that of the target on 20% of trials.

Participants undertook 60 neutral trials, which was preceded by 10 trials in which no data was collected (practice trials). Cued trials were preceded by 15 practice trials; with two blocks of 100 trials with a cue-duration of 100ms and two blocks of 100 trials where the cue was presented for 1200ms. Block order was counterbalanced across participants.

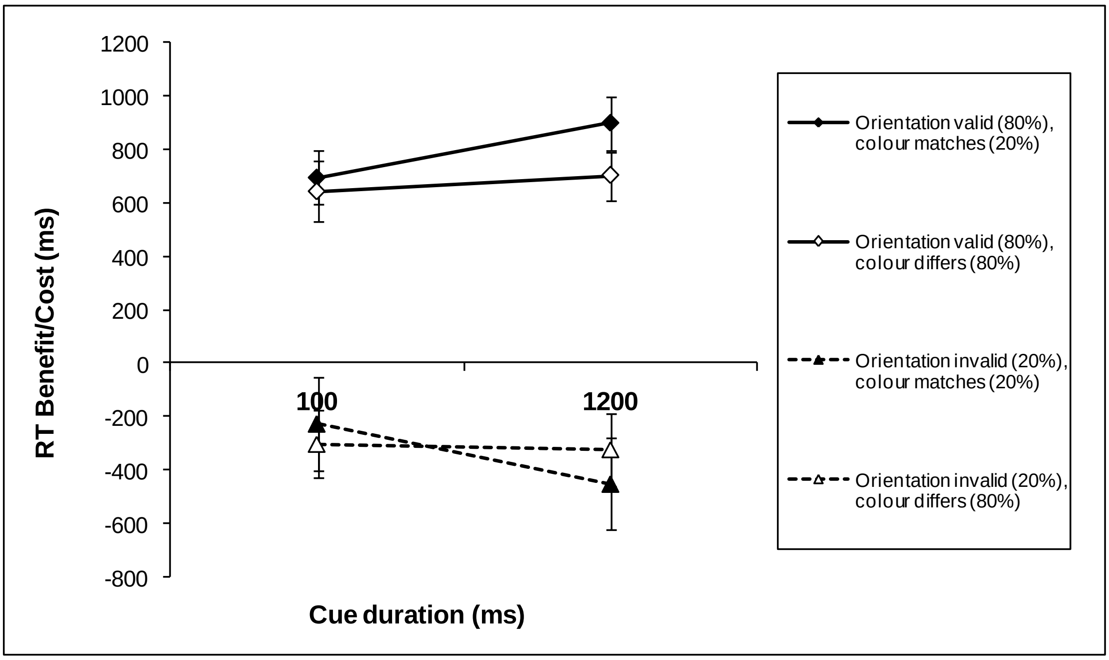

Figure 4.4. Mean RT Benefits/Costs (+/- one standard error) from Experiment 4.3, separated by the validity of the predictive cue feature (orientation), contra-predictive colour status (whether it matches or differs with the target) and cue duration.

4.3.3: Results

RT Cost-Benefits. The data were cleaned as in Experiment 4.2. As previously, the neutral condition was used as a baseline and the RT Benefits (when the predictive feature was valid) and RT Costs (when the predictive feature was invalid) were calculated for each participant by subtracting median RTs in the relevant cued condition from median RTs on neutral trials. Group means are shown in Figure 4.4.

A three-factor ANOVA (cue duration, orientation validity, status of contra-predictive cue colour) found a main effect of orientation validity ($F(1,19)=56.9$, $p<0.001$, partial $\eta^2=0.75$), as well as an interaction between orientation validity and cue duration ($F(1,19)=6.4$, $p=0.02$, partial $\eta^2=0.252$). There was also a borderline significant interaction between orientation validity and the status of the contra-predictive cue colour ($F(1,19)=4.1$, $p=0.057$, partial $\eta^2=0.178$) and a robust three-way interaction ($F(1,19)=5.6$, $p=0.029$, partial $\eta^2=0.227$).

To unpack the last three-way interaction, the data were split by the validity of the predictive feature (orientation). Analysis of the RT Benefits showed main effects of cue duration ($F(1,19)=4.8$, $p=0.041$, partial $\eta^2=0.202$) and the status of contra-predictive cue colour ($F(1,19)=5.9$, $p=0.025$, partial $\eta^2=0.237$). Compared to the neutral condition, there was a larger benefit from longer (an effect of 802ms) than shorter cues (an effect of 670ms). There was an increased benefit when the colour of the cue matched the target (an effect of 798ms) compared to when it did not (an effect of 673ms). There was also a borderline significant cue duration x status of contra-predictive cue colour interaction ($F(1,19)=3.8$, $p=0.065$, partial $\eta^2=0.168$). The benefit from when the cue colour matched the target compared to when the cue colour differed increased following longer cues (100ms cue, an effect of 53ms, $p=0.376$; 1200ms cue, an effect of 198ms, $p=0.009$). Analysis of the RT Costs indicated a borderline significant interaction between cue duration and the status of contra-predictive cue colour ($F(1,19)=3.5$, $p=0.076$, partial $\eta^2=0.156$). This interaction was driven by differential effects of cue colour between short and long cues. Following 100ms cues, there was a relative benefit from the cue colour matching the target compared to when there was a mismatch (an effect of 76ms, $p=0.449$). When cues were longer (1200ms), there was an added cost when colour of the cue matched the target compared to when it did not (an effect of 128ms, p=0.241).

RT Cost-Benefit: Comparing Experiments 4.2 and 4.3. To examine how changing the predictive probability of the 'other feature' influenced its effects, I compared the effect of 100ms cues with orientation as the predictive feature in Experiment 4.2 (cue colour matched the target at chance) with the effects in Experiment 4.3 (cue colour matched the target on 20% of trials). For parsimony, only significant main effects and interactions involving experiment will be reported. A mixed-design, three-factor ANOVA (experiment number, orientation validity, status of non-predictive colour) revealed an interaction between the status of the non-predictive cue colour and experiment number (F(1,36)=6.1, p=0.018, partial η^2=0.145) as well as a significant three-way interaction (F(1,36)=6.7, p=0.014, partial η^2=0.157). Unpacking the latter interaction, the only cueing effect that varied significantly across experiments was a reduction from Experiment 4.2 to Experiment 4.3 in the cost from the cue colour not matching the target when the orientation of the cue was valid (a difference of 388ms, p=0.016); no other comparisons reached significance (ps>0.3). The variation across experiments suggests a larger stimulus-driven effect was present when the cue colour matched the target at chance compared to when it was contra-predictive (e.g., matching the target on 20% of trials).

Accuracy. There was no evidence of a speed-accuracy trade-off. Mean accuracy is shown in Table 4.1.

4.3.4: Discussion

As in Experiment 4.2, there was a robust effect of the colour of the cue on search RTs when the orientation of the cue correctly predicted the target, with a benefit when the cue and target shared the same colour compared to when they differed. Cue colour affected search behaviour even though it was contra-predictive, only matching the target on 20% of trials (compared to 50% in Experiment 4.2). The effect increased with increasing cue duration, suggesting that participants were unable to ignore or inhibit cue colour even with more time available to process the cued information. While these findings suggest that the colour of a visual stimulus (e.g., the cue) presented prior to a search affects RTs automatically, reflexively directs attention towards search stimulus matching it in colour (cf. Posner et al., 1982), the effect decreased when the predictive feature (orientation) was invalid. There was also a trend toward differential effects of cue colour at short and long cue durations. Following short cues, search was facilitated when the cue colour matched the target compared to when there was a mismatch (mirroring the effect of cue colour from valid cues). When the cue was presented for longer (1200ms), however, search was slowed when the cue colour matched the target, in comparison with when colour of the cue and target differed. Comparisons across Experiments 4.2 and 4.3 reveal stronger effects when cue colour only matched the target on 50% of trials (Experiment 4.2) compared to when the cue and target could were the same on only 20% of trials (Experiment 4.3). This reduction suggests strategic processing of the cue colour was evident in Experiment 4.2, with participants attending to the colour information despite the lack of a benefit associated with doing so (cf. Laarni, 2001).

The results of Experiment 4.3 suggest a level of automatic processing of cue colour. However, what level of visual processing is the non-predictive information affecting? Participants could be coding the cue as an object, with the unattended feature transferred into working memory in conjunction with the attended cue information (cf. Soto & Humphreys, 2009). Previous studies have proposed that cueing information about the target is transferred into working memory, guiding search in this manner (e.g., Huettig & Altmann, 2005; Moores et al., 2003). Therefore, participants could have memorised the predictive task-relevant cue information, with the non-predictive feature coded as part of the process. The features of the whole cue would affect RTs, whether they are attended to or not. Alternately, the non-predictive colour of the cues in Experiment 4.3 could have affected search by priming the visual system to expect a target with the same colour, in a similar fashion to the facilitation evident from repeating a target-feature trial-on-trial (e.g., Becker & Horstmann, 2009; Kristjánsson, 2006; McBride et al., 2007). Indeed, a carry-over effect of target colour has been demonstrated when colour was irrelevant to the search (Kristjánsson, 2006; McBride et al., 2007).

The effects of cue colour in Experiment 4.3, however, were dependent on the validity of the predictive feature, suggesting differential processes occur on valid and invalid trials. When the orientation of the cue was valid, there was an added facilitation when the colour also matched the target relative to when it did not. However, when orientation was invalid, a different pattern of effects emerged. At short cue durations, the non-predictive, priming effects of the cue mirrored that when the cue was valid (e.g., a facilitation when cue colour matched the target compared to when it differed). Following long cues there was a larger cost when the colour of the cue matched the target, compared to when it did not. If the priming effects of the cue were automatic, affecting RTs to the same degree across both valid and invalid trials, then, following an invalid cue (e.g., the orientation of the cue would be invalid), the colour of the cue would initially guide search towards stimuli sharing the colour of the cue (cf. Becker & Horstmann, 2009). If the colour of the cue and target matched, this process would oppose and lessen the effect of the invalid feature of the cue. On the other hand, a mismatch would increase the effect of the invalid predictive information in slowing search. Similar effects would be expected during the later stages of search, where attention may be re-oriented towards stimuli not matching the predictive feature of the cue (e.g., orientation), but included in the target-containing subset. A match between the cue's colour and the target would guide attention towards the target compared to when the cue and target colour differed. If the effects from the cued colour on invalid trials were comparable to those on valid trials, similar priming effects would also be expected – e.g., facilitation when the cue and target match in colour compared to when they differed. This was not reflected in the data.

One proposal is that the effect of cued colour degrades during the longer RTs of invalid trials (cf. Vickery et al., 2005; Wolfe et al., 2004). Priming would have only affected the early stages of search, with less effect later in the process (e.g., when attention is re-oriented to the target-containing subset of uncued stimuli). Priming effects of the colour of invalid cues would therefore have a reduced effect on RTs compared to when the cues were valid. A similar temporal argument could be made for any non-predictive effects arising from retaining the cue stimulus in working memory (cf. Soto, Rotshtein, Hodsoll, & Humphreys, 2008). Effects from the colour associated with a stimulus retained in working memory may be short-lasting (Soto & Humphreys, 2009), with colour having no influence at longer SOAs (see Olivers, Meijer, & Theeuwes, 2006). However, from both hypotheses I would expect similar diminishing effects on invalid trials following both short and long cues. Again, this is not substantiated by the data, with priming effects only evident following short cues (100ms) and the effects of cue colour switched when cues were presented for longer (1200ms). An alternate proposal is that the long cue duration and the extended RTs on invalid trials allow enough time for the participant to become aware of the contra-predictive nature of the cue colour. Participants could then switch to expecting the target with the opposite colour to cue (e.g., Kean & Lambert, 2003; Neely, 1997; Posner, 1982). Whichever account in proposed, it would be wise to be cautious given that invalid trials on which the colour of the cue matches that of the target are based on relative small amounts of data (4% of the trials).

4.4: General Discussion

The three experiments reported here show that effects of pre-cueing the target in a visual search task were influenced by the physical nature of the cue. In all experiments, a visual cue predicted the colour or orientation of the following target in conjunction search, with the cueing information having 80% validity. Experiment 4.1 established a baseline where both physical and predictive properties from cues were the same (e.g., all information was predictive), varying the cue duration from short (100ms) to long (1200ms) cues. Compared to an uncued neutral condition, search was facilitated (a benefit) when cues matched the target while RTs were longer (a cost) on trials when the cue and target did not match. There was a larger modulation of attention when colour rather than orientation cues were given. A larger benefit from valid colour cues was present across all cue durations, however an increased cost from invalid orientation cues was only evident when cues were presented for 200ms. The data shows a stronger guidance when the colour of the cue matched that of the target. However, it is difficult to delineate whether the advantage was due to priming from the physical properties of the cue or differences in the processing of the predictive (colour and orientation) cues. In Experiment 4.2, predictive information associated with the cue was again presented visually prior to search, however a secondary cue feature was introduced that randomly matched the target. In one experimental session, the colour of the cue (a coloured bar) was predictive while its orientation was not, while the opposite was true in an alternate session (e.g., the orientation of the line was predictive, the colour non-predictive). There were sizeable effects from this ‘other’ non-predictive feature, especially when there was a valid orientation cue and the non-predictive feature was colour. At both cue durations (100ms and 200ms), a strong facilitation was evident when there was a match between the non-predictive feature and the target, compared to when there was a mismatch. The non-predictive, priming effects from cue colour brought performance with orientation-predictive cues to that found with colour-predictive cues alone. This suggests that the stronger effect of visual colour cues (see Experiment 4.1) could be a consequence of automatic priming rather than top-down processing of the cue (cf. Anderson et al., 2010). In Experiment 4.3, similar priming effects from the colour of the cue were still evident when the non-predictive attribute matched the target on only 20% of trials, while the predictive feature (orientation) remained at 80% validity. Cued colour affected search following both short and long cues, however the effects were only reliable when the orientation of the cue was valid suggesting that priming effects were not automatic. There was a reduction in the effects of cue colour when it was contra-predictive compared to when cue colour matched the target at chance, revealing that a level of strategic processing was present when the colour of the cue randomly matched the target (on 50% of trials, in Experiment 4.2).

4.4.1: Colour advantage

The results revealed similar stronger stimulus-driven guidance from the colour of a cue when there was a predictive link between the colour of the target and cue. The priming effects remained when the colour of the cue was contra-predictive

(Experiment 4.3), but there was then a reduced effect compared to when the colour and target matched at chance (Experiment 4.2). This suggests the advantage for colour cueing found previously (Anderson et al., 2010) can be explained, at least partly, by differences in how the physical nature of the cue is processed. Colour has been shown to be perceived early than orientation (Moutoussis & Zeki, 1997), offering evidence towards an early benefit for guidance following a colour cue. Indeed, stronger guidance from cue colour, particularly following valid cues, was manifest following the shortest cue duration (100ms). The level of processing following the early detection of colour information, however, and how this is translated into guidance is not clear. Colour priming has been shown to direct eye movements (Becker & Horstmann, 2009), with effects from colour even when irrelevant to the search task (Kristjánsson, 2006; McBride et al., 2007). The robust advantage for colour cueing when both predictive and non-predictive would be consistent with increased bottom-up priming of the visual system enabling more efficient and speedy processing of the relevant stimuli (see Becker & Horstmann, 2009). An alternate proposal is that guidance following cues is a consequence of the information being coded into working memory prior to the search (cf. Moores et al., 2003). Featural information maintained in working memory has been shown to affect RTs with a stronger effect from colour than shape cues (Soto et al., 2005). There is also evidence of an effect from the colour of a cue when colour was not the feature that had to be memorised but was present for the to-be-memorised shape (Soto & Humphreys, 2009). It is possible that the larger effects from colour of the cue, whether it is predictive or non-predictive, could involve both priming and working memory processes.

4.4.2: Invalid cues

Whatever the mechanisms for the colour advantage, the effects were reduced following invalid cues compared to the effects on valid trials (Experiments 4.2 and 4.3). This suggests that the effects either decrease during the longer RTs on invalid trials or are contingent on the validity of the predictive cue feature, or a combination of the two factors. The temporal proposal fits with processing of non-predictive features occurring via mechanisms involving either priming or working memory, both of which have shown to be short-lived (priming, Vickery et al., 2005; Wolfe et al., 2004; working memory, Soto & Humphreys, 2009; Olivers et al., 2006). On the other hand, it may be that during invalid trials participants, after searching the cued subset, become aware of the invalid nature of the cueing information (cf. Posner et al., 1982) and use this knowledge to re-orient attention towards the target-containing subset. Participants therefore reject the predictive information from the cue in response to the absence of the cued target. If the features of the cue were coded together (cf. Soto & Humphreys, 2009), the effect of the non-predictive information would also be discarded. These two proposals could be tested by varying the number of stimuli in the search task, thereby either increasing the length of valid trials or reducing the length of invalid trials (cf. Anderson et al., 2010). The temporal hypothesis would suggest that effects from the non-predictive colour of the cue would negatively correlate with the number search items (e.g., decrease with increasing display size). Similar effects across array sizes, however, would offer evidence that participants reject all information once the cues have been identified as invalid, regardless of the time taken to complete the search.

4.4.3: Conclusions

Stronger priming effects have been involved in the larger modulation of RTs by visual colour cues. These effects occur early on in processing the cue, which could be due to early detection of the cue colour (see Moutoussis & Zeki, 1997). The mechanisms involved could be due to priming by the physical properties of the cue or effects associated with retaining the cue stimulus in working memory. Whichever processes are involved, priming from visual cues should be taken into consideration when interpreting the effects of visual cueing on RTs.

CHAPTER 5

Conjunction Search Without Target-specific Knowledge: an Eye Movement Study

5.0.1: Abstract

Two experiments examined featural and spatial guidance on behavioural performance and eye movements during search for two possible conjunctive targets. In the absence of foreknowledge about target identity, Experiment 5.1 showed that search was facilitated and there were increases in target-fixations when unequal groups of distractors were presented – eye movements were initially directed to smaller subsets of distractors. The bias increased at fixation 2 when the subset shared the target's colour and decreased when it matched its orientation. Search was preferentially guided by stimuli colour, with stronger grouping between same-coloured stimuli and early coding of target-colour. Experiment 5.2 used trials with balanced ratios but adjacent distractors differing either in both colour and orientation or in two homogenous groups. Search was slowest with heterogeneous displays, while reaction times (RTs) were shortest when the target differed from the local distractor group in the orientation compared with when they differed in the colour dimension. On homogeneous trials, early guidance was evident from the target but only when there was a local colour disparity. This initial advantage was not reflected in overall performance, which suggests that stronger grouping effects may aid search when targets and distractors match in colour. Overall, the findings indicate that search was influences to a grater extent by colour than orientation, for both target and distractors..

5.0.2: Introduction

In day-to-day life, the way we search the world is affected both by the nature of the items in our visual field and how they are related to what we are looking; for example, when looking for your friend in a crowd, your eye might be drawn to people similar in height and hair colour. Experimentally, the processes behind such real-life examples has been investigated using the visual search paradigm, where participants look for a target randomly placed amongst an array of distractors of varying number and form. A plethora of studies have investigated how the physical nature of the search items (bottom-up factors) have affected behaviour (see, Müller & Krummenacher, 2006, and Wolfe, 1998, for reviews), and how these effects are modulated by the knowledge of what you are looking (top-down processes; e.g., Eimer & Kiss, 2008; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Effects of top-down guidance have been examined with both efficient and inefficient search (e.g., with complex displays), while effects of bottom-up guidance have primarily been studied when the search-critical feature is efficient (see Müller & Krummancher, 2006). Few researchers, however, have focussed on bottom-up search behaviour (i.e., without top-down guidance) when search is inefficient (e.g., when the target is defined by a conjunction of features). The current study requires participants to search for two possible conjunction targets, thereby minimising target-specific bias (cf. Linnell & Humphreys, 2007) and as a consequence top-down, user-controlled guidance, while manipulating both the featural and spatial relationship between distractors. The experiments, therefore, demonstrate how stimulus-driven featural and spatial grouping can modulate search with complex displays.

Search for a conjunction of features is typically dependent on the number of stimuli in the search array (see Wolfe, 1998). However, a number of studies have shown the relative number of each type of distractor also influences behaviour, with search more efficient at extreme distractor ratios (termed a ‘ratio effect’; see 1.5.1 for details). Within the framework of models such as Guided Search Theory (GST: Wolfe, 1994; Wolfe, Cave & Franzel, 1989; see 1.4.1 for details of the model), search may be guided to stimuli in the smaller subset of distractors as they possess higher salience than items in the larger subset.

While stimulus-driven processes may direct attention towards the type of distractor in the minority, top-down factors, such as knowledge of the target, also affect search behaviour. A number of studies have found attention to be directed preferentially towards stimuli sharing a feature with the target (see 1.5.3 for details) indicating that attention is biased towards distractors by information about the target (e.g., Findlay, 1997). Guidance driven by the nature of the target could be seen to affect the preference for searching the smaller subset of stimuli outlined previously (e.g., Sobel & Cave, 2002). Participants typically search for a known target in such studies and may prioritise distractors matching the target in one of the target-defining dimensions (e.g., colour or orientation). As well as guidance based on distractor salience, search may therefore be directed towards smaller subsets of stimuli due to the salience of the target item. To reduce such target-specific bias, the current study examines the effect of manipulating the ratio of distractors when participants did not know which target would be present on each particular display. Any residual preference towards distractor subset should then be directly attributed to guidance from distractor items.

In our task, participants searched for two possible targets, with only one present per trial. Each target shared a feature – colour or orientation – with each type of distractors and was equally likely to be present, thus removing top-down biasing of attention towards distractors with the same colour or orientation with the target. Other studies have used two-target methodologies, but the targets have been chosen either to alter the nature of the search (e.g., contrasting ‘easy’ and ‘more difficult’ targets, Heinke, Humphreys & Tweed, 2006) or have involved odd-one-out tasks where the targets were defined by a single feature (e.g., Krummenacher, Müller & Heller, 2002). Almost no other researchers (cf. Linnell & Humphreys, 2007) have investigated conjunction search when participants were ignorant of the nature of the target of the next trial, a methodology that allows the present study to isolate the results of distractor-specific guidance.

Traditional measures of search behaviour, such as reaction time (RTs) and accuracy, provide overall measures search efficiency, but do not provide information about the microgenesis of search as it takes place. A finer-grained analysis is offered through measuring eye movements. While a number of studies have found that fixations are more likely to be directed towards distractors sharing a feature with the target than to other items (e.g., Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006; Rutishauser & Koch, 2007; Shen et al., 2000; Williams & Reingold, 2001), the strength of guidance depends on the discriminability within each dimension (Williams & Reingold, 2001) as well as the ratio of distractors (Shen et al., 2000). Shen et al. found that eye movements were guided towards a subset of stimuli with the same colour as the target when they were in the minority, and a similar bias towards fixating shape stimuli was evident when the shape-defined subset was smaller, a bias consistent with the subset search proposed by Sobel and Cave (2002).

In the present study, I measured how response and eye movement behaviour during a conjunction search were affected by varying the ratio between distractors (Experiment 5.1). This was undertaken to investigate how any bias towards fixating the smaller subset of distractors would progress without top-down bias from prior knowledge about the search target. During pilot studies, the colour of stimuli (cf. Bacon & Egeth, 1997) were adjusted to balance search efficiency for colour- and orientation-defined targets (See Experiment 2.4 for details) to avoid dimension-specific bias (see Williams & Reingold, 2001). These stimuli were then used in the colour-orientation conjunction search. RTs and errors were recorded across differing distractor ratios, along with the stimuli fixated during the first two eye movements, enabling me to build a picture of how a stimulus-driven bias towards smaller-group search affects both overt movements of attention and ‘whole system’ performance (measured through RTs and errors).

To investigate the guidance when top-down as well as featural biases were at a minimum, in Experiment 5.2 I kept the distractor ratio balanced while varying the spatial relationship between distractor types. Grouping of adjacent distractors has been shown to be an important factor during conjunction search (e.g., Poisson & Wilkinson, 1992; Treisman, 1982; see 1.5.2 for details). Poisson and Wilkinson took this as evidence of spatial groups being processed as simple units irrespective of the numbers of distractors present. In contrast, Kim and Cave found similar patterns of search irrespective of whether the stimuli were positioned randomly (Kim & Cave, 1995) or separated into two homogenous groups (Kim & Cave, 1999), with attention directed towards distractors with the target-colour in both studies.

Experiment 5.2, however, allowed direct comparison between behaviour in heterogeneous and homogeneous search conditions without target-specific bias. In Kim and Cave (1999), it is possible that the top-down cue was sufficiently strong to override bottom-up grouping effects. Moreover, and unlike prior studies, the relative discriminability of the features within the defining dimensions was controlled. The trials matched those of the balanced ratio condition in Experiment 5.1, but now adjacent distractors either alternated in type or were manipulated so that the target differed either in colour or orientation from the adjacent homogenous group of distractors.

Experiment 5.1: Varying the Distractor Ratio

5.1.1: Introduction

Experiment 5.1 investigated effects of varying the distractor ratio on conjunction search with reduced top-down bias, with both behavioural and eye movement data recorded. To reduce top-down, target-specific guidance (cf. Williams & Reingold, 2001), I used two possible targets (blue horizontal and green vertical bars) with distractors that shared one feature with each (blue vertical and green horizontal bars). The stimuli matched those from the conjunction search in the pilot study (see Experiment 2.4). Search could not therefore be guided by a particular feature of the target (cf. Linnell & Humphreys, 2007). I introduced three ratio conditions, two with unequal numbers of each type of distractor and one where the ratios were balanced. For RT data, I expected to find search to be facilitated when the target was in the minority set of distractors (cf. Sobel & Cave, 2002). The same should hold for the eye-tracking data, with increased bias towards fixating both the target and the smaller group of distractors when the ratio was not balanced. Recording the type of stimuli fixated also allowed me to look at whether attention remained within one class of stimuli after the first fixation.

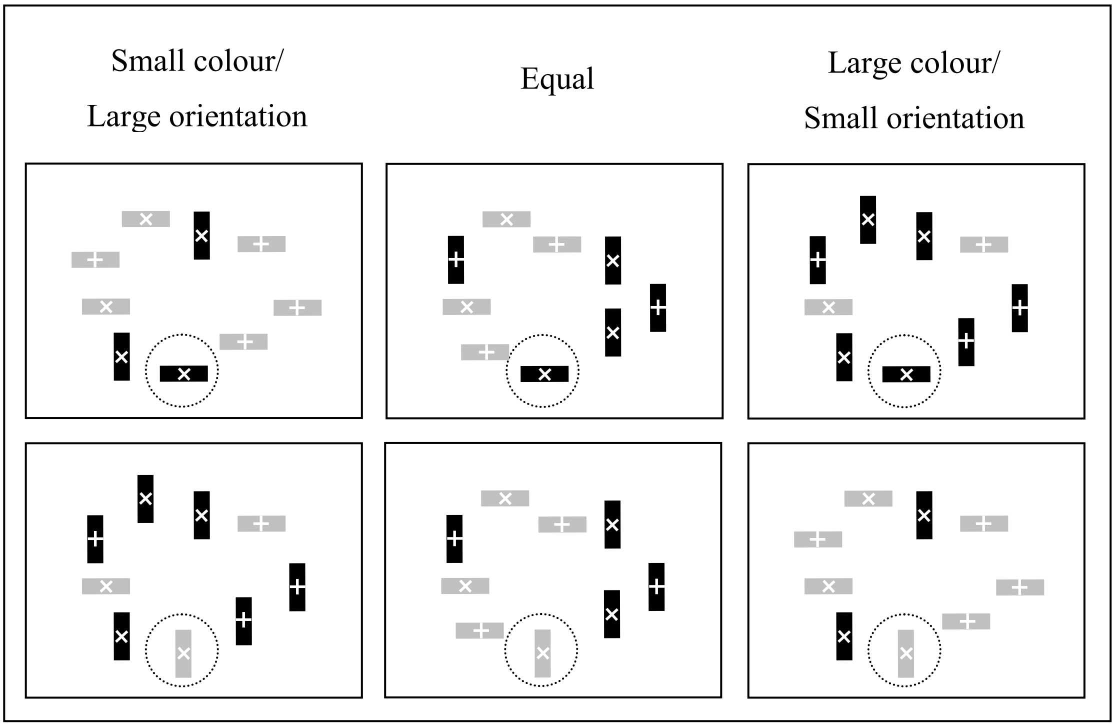

Figure 5.1. Illustration of the distractor ratios used in Experiment 5.1, with arrays labelled by display type. The ratios varied from two blue vertical and six green horizontal distractors (2BV, 6GH) to 4BV, 4GH to 6BV, 2GH. Blue stimuli are shown in black, green in grey, light grey symbols and light grey background in white. Displays were coded according to the size of the group of distractors (Small or Large) having the same colour/orientation as the target.

5.1.2: Method

The methodology matches that of the conjunction task of Experiment 2.4, with the exceptions outlined below.

Participants. Thirty-nine University of Birmingham students, eight male, 31 female, aged 18-30 (average 20.47) took part.

Design. There were two main independent variables: distractor ratio (see Procedure section) and target type (green horizontal, blue vertical).

Apparatus. Search items were presented and behavioural responses collected as in Experiment 2.4. However, eye movements were also recorded using an SMI infra-red Remote Eyetracking Device III (SMI RedIII; SensoMotoric Instruments GmbH, Germany 2002-2004). The gaze position accuracy was 0.5°, with sampling rate 50 Hz. The eye-tracking camera was linked to a separate PC to the one displaying the search stimuli. IViewX (version 1.07.00) software was used to calibrate the camera and collect data. E-Prime software on the display PC was synchronised via an ethernet cable with the IViewX software.

Procedure. Due to high error rates during pilot studies, participants were informed of the nature of two possible targets prior to the experiment. However, they were also told that either target was equally likely on each trial. Visual reminders of the targets were also presented adjacent to the computer monitor but only during practice phase, when eye movements and behavioural data were not recorded. On each trial, a fixation circle was presented first for 1,000ms, before a 100ms inter-stimulus interval (ISI) which was followed by an array of stimuli with one target and eight distractors. Unlike Experiment 2.4, the ratio of the two distractor types was manipulated as follows: two blue vertical bars and six green horizontal bars (2BV, 6GH); 4GV, 4GH; and 6BV, 2GH (see Figure 5.1 for examples). The target was either a blue horizontal (50%) or green vertical bar and both the distractor ratio and target varied randomly trial-on-trial. There were between nine and 16 practice trials followed by a block of 72 experimental trials.

5.1.3: Results

The data from three participants were discarded due to a mean accuracy of less than 90%. To maximise the number of trials per condition, the data were pooled across target type. The ratios were therefore coded according to the size of the distractor group sharing its colour or orientation with the target. As the two dimensions co-varied, the resulting display types were: Small colour/large orientation, Equal, Large colour/small orientation. This meant, for example, a trial with a blue horizontal target and a 2BV, 6GH ratio was coded as Small colour/large orientation condition. The same coding would be used when the green vertical target was surrounded by a distractor ratio of 6BV, 2GH. See Figure 5.1.

RTs. Data were cleaned as previously. Trials that were inaccurate were removed and median RTs in each condition for each participant were calculated. Group means are shown in Figure 5.2. A one-factor ANOVA (display type) revealed a borderline significant main effect of display type (F(2,70)=2.9, p=0.057, partial η^2=0.079). Pair-wise comparisons showed that RTs were significantly shorter in the Small colour/large orientation condition compared to the Equal condition (difference of 119ms, p=0.015). There was a trend towards a similar facilitation effect for the Large colour/small orientation condition (difference of 76ms, p=0.115). There was no difference in RTs between the two extreme display types (difference of 43ms, p=0.432).

Accuracy. There was no speed-accuracy trade-off. The mean accuracy data are shown in Table 5.1.

Experiment	**Display type**		
	Small colour/large orientation	**Equal**	**Large colour/small orientation**
5.1	95	97	96
	Mixed	**Orientation segmentation**	**Colour segmentation**
5.2	97	97	98

Table 5.1. Mean percentage of correct responses from both Experiment 5.1 and Experiment 5.2 divided by display type.

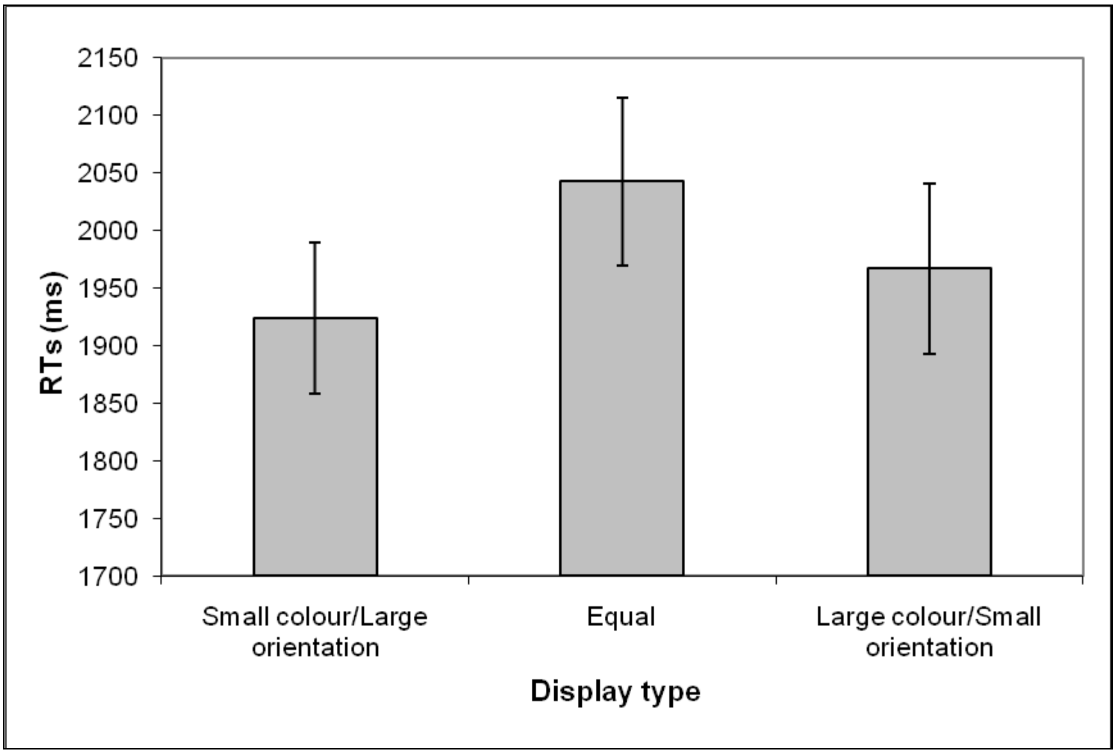

Figure 5.2. Mean (+/- one standard error) of median RTs from Experiment 5.1, divided by display type. The ratio was coded to indicate the size of the distractor group sharing its colour/orientation with the target (see Figure 5.1).

Eye movements. For each trial, eye movements were recorded from the onset of the search array until response. A fixation was classified when the speed of the eye movement remained below 50 visual degrees per second (°/s) for 100ms. Data recorded during eye-blinks and off-screen eye movements were discarded, as were fixations detected within 80ms of array onset (see van Zoest, Donk, & Theeuwes, 2004). As with RT data, I removed inaccurate trials and those with RTs more than 5000ms. The number of fixations per trial varied depending on search efficiency, however at least 80% of the trials from each participant contained two fixations or more. Only the first two fixations were analysed, therefore, with trials with fewer fixations removed. Data from three participants were eliminated due to problems with response accuracy (see RT analysis) and a further participant was removed due to technical issues with eye-tracking calibration.

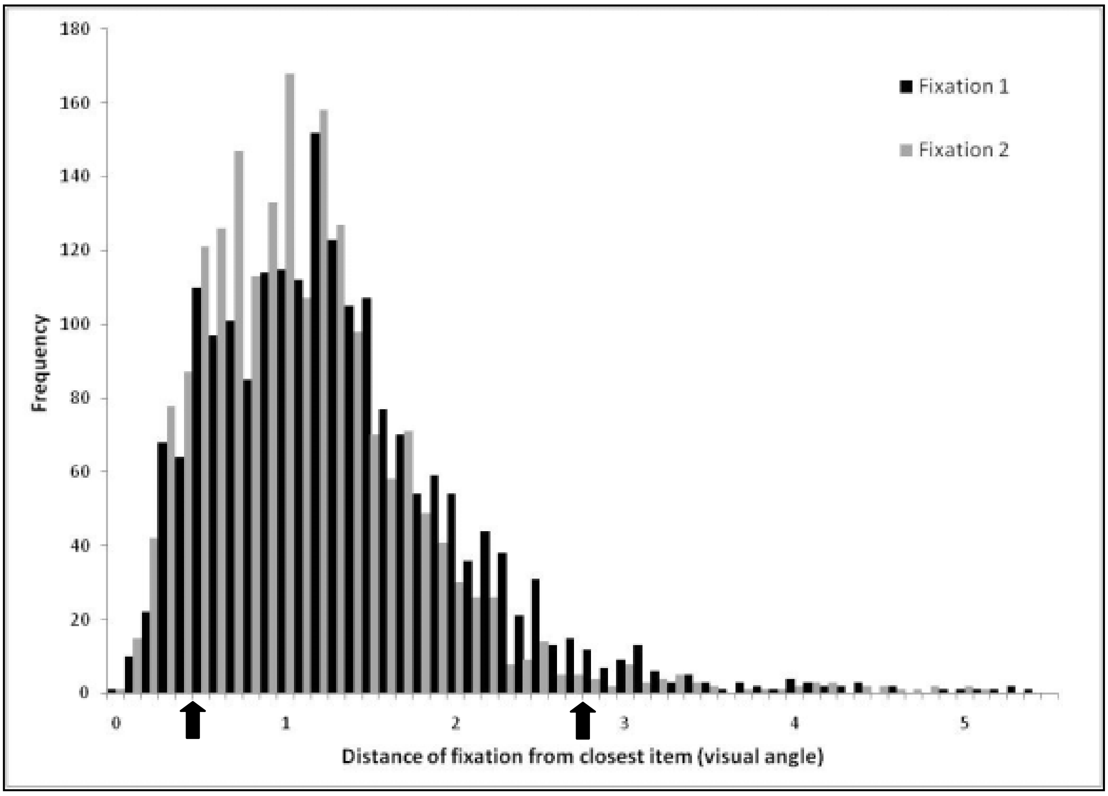

Figure 5.3. Distribution of distances from the locations of first and second fixations to the nearest item in Experiment 5.1 (in degrees of visual angle). Arrows indicate the spatial resolution of the eye-tracker (0.5°) and average inter-item distance (2.8°).

Fixation-item distances. Following Williams & Reingold, 2001, for each fixation I calculated the identity of the nearest stimulus. However, this indication of which items were fixated may not be reflecting search behaviour. Prior studies have shown that fixations are often directed between items, processing the items as a group rather than individually (e.g., Findlay & Gilchrist, 1997; Zelinsky, Rao, Hayhoe, & Ballard, 1997). To assess the accuracy of attributing the nearest item to the fixation, I calculated the Euclidian distance between the location of fixations as measured by the eye-tracker in Experiment 5.1 and the centre of the nearest stimuli. The distributions of first and second fixations are shown in Figure 5.3. These were then compared with two thresholds; the distance of the centre of the item centre to item edge (a visual angle of 0.5°); and to half the mean distance between adjacent search items (a visual angle of 1.4°). The former comparison indicates whether fixations were directed to the items themselves. The second offers evidence as to whether fixations were instead guided within the penumbra of the nearest item, which may give more validity that these stimuli were being processed by this eye movement, perhaps by covert attentional processes (see 1.2.2).

Threshold comparisons. One-sample t-tests indicated that both fixations 1 and 2 did not overlap the physical positions of the nearest item (e.g., within the threshold of 0.5°: fixation 1, mean distance=1.28°, $t(1985)=45.7$, $p<0.001$; fixation 2, mean distance=1.1°, $t(1985)=38.8$, $p<0.001$, both one-tailed). The second threshold was half average distance between items (a distance of 1.4°). Distances from both fixations were significantly below this threshold (fixation 1, $t(1985)=-7.3$, $p<0.001$; fixation 2, $t(1985)=-20.8$, $p<0.001$, both one-tailed). While neither fixation were likely to land on the search items, the majority were directed within the penumbra of the nearest stimuli. This suggests that eye movements were inaccurate but were programmed more towards specific stimuli rather than a group of items (cf. Zelinsky et al., 1997).

Spatial accuracy. It is also necessary to question the suitability of the spatial accuracy of the eye-tracking set-up of current display. The RedEye III can determine eye position within half a visual angle and therefore indicate fixation location +/- 0.5°. The items used here were 1° long with a mean inter-item difference is 2.8°. Especially with regard to deciding whether fixations landed on the search items, the accuracy was therefore not ideal. That said, the majority of first and second fixations were directed within the penumbra of the nearest item (see above). T-tests also indicate that the second fixations were closer to the nearest item than the initial fixations (t(1985)=8.898, p<0.001). This suggests that, while not optimal, the eye-tracking set-up was sensitive enough to measure the increased accuracy towards fixating array items as search developed (cf. Zelinksy et al., 1997).

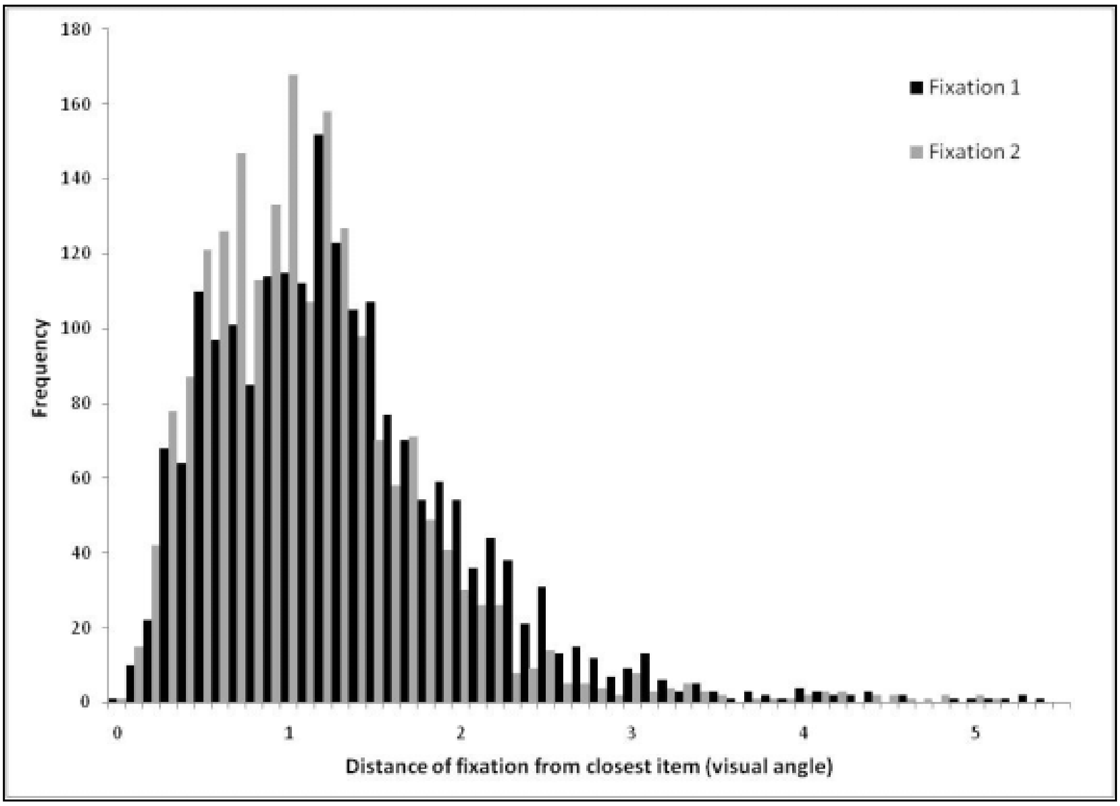

Figure 5.4. Distribution of the duration of fixations (in ms) from Experiment 5.1.

Fixation durations. As well as the spatial accuracy of the eye tracking, the temporal sensitivity of the set-up needs examination. The RedEye III ran at 50Hz, sampling eye movements every 20ms. For this temporal resolution to be adequate, fixation durations should reflect those established by previous researchers. The durations of first and second fixations on all trials in Experiment 5.1 are shown in Figure 5.4. Previous studies have shown that fixation durations typically vary between 200 and 500ms (Hoffman, 1998; Hooge & Erkelens, 1998; Luria & Strauss, 1975). The mode values for both first and second fixations in the current study was 200ms and the majority were shorter than 500ms (fixation 1, t(1985)=-25.93, p<0.001; fixation 2, t(1985)=-17.383, p<0.001). This suggests that the temporal sensitivity of the set-up was suitable for current purposes.

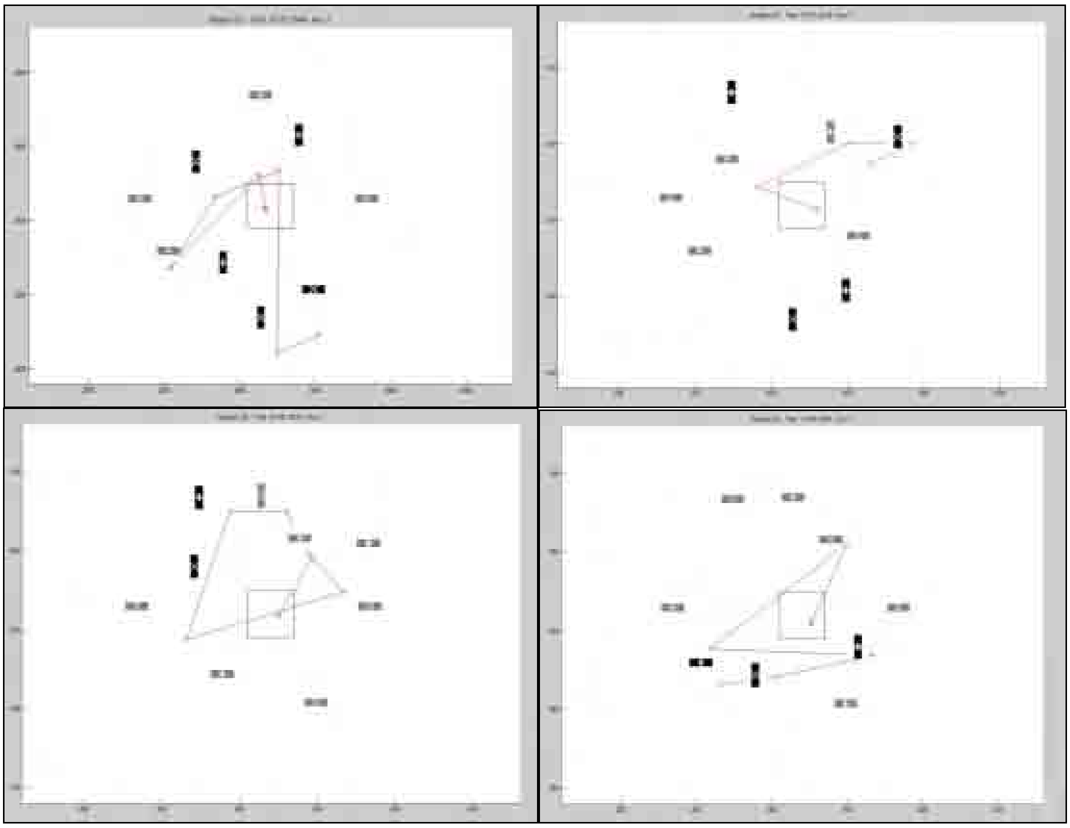

Figure 5.5. Scan paths of eye movements in Experiment 5.1.

Qualitative measures. A further measure of the suitability of both the spatial and temporal characteristics of the eye tracking set-up is an examination of typical scan-paths during search (cf. Zelinksy et al., 1997). Figure 5.5 shows examples of the scan paths recorded during Experiment 5.1. Crosses indicate fixations, with lines linking consecutive fixations. Initial fixations can be seen to be directed towards individual items but their positions rarely overlap the items themselves. Subsequent fixations were more accurate (Findlay & Gilchrist, 1997). A similar pattern is evident from a scatterplot of locations (see Figure 5.6) with fixations gravitating towards the item positions from fixation 1 to 2. These qualitative indicators match the pattern outlined in the threshold analysis undertaken previously, with guidance towards items more evident at fixation 2 versus fixation 1.

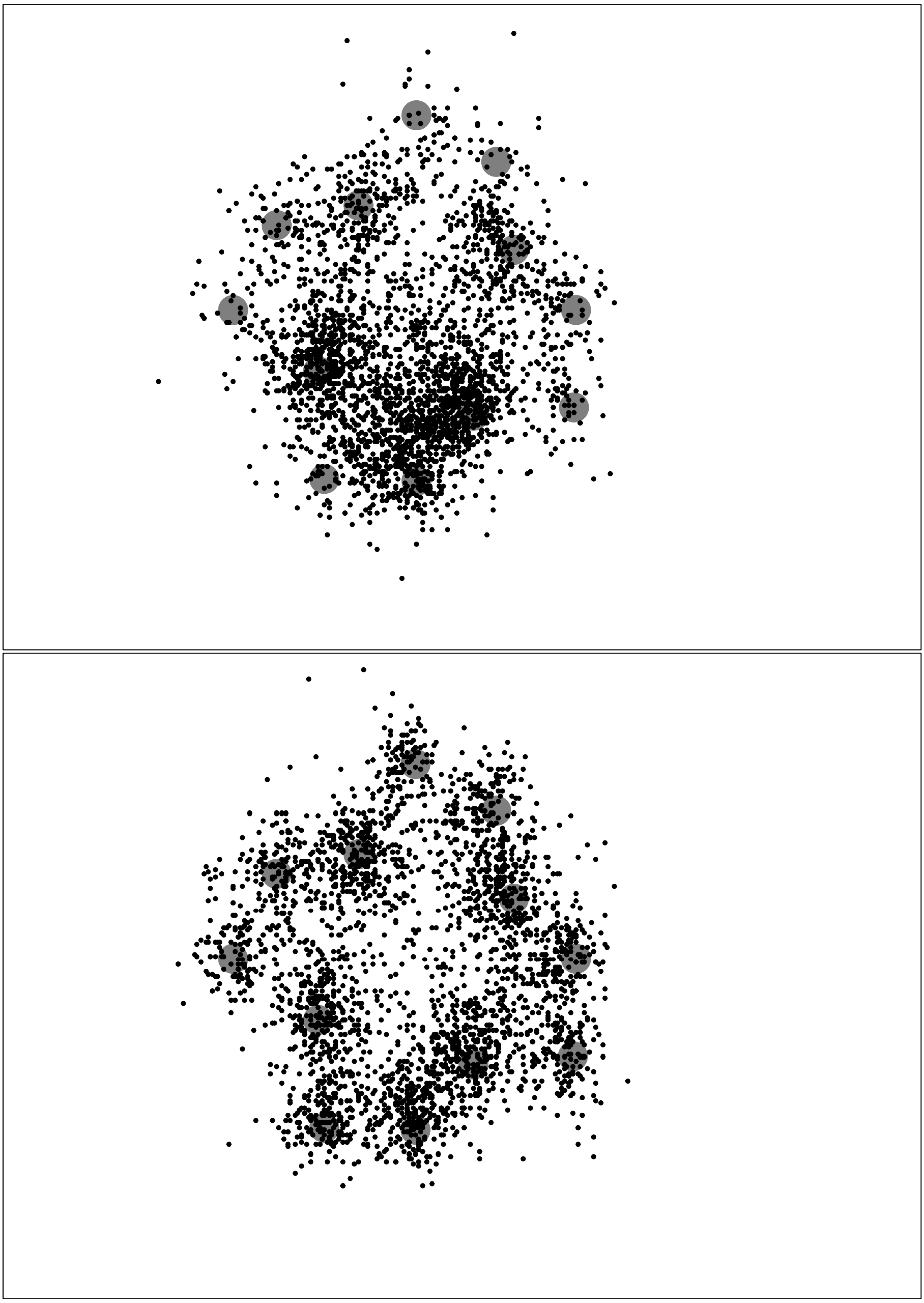

Figure 5.6. Locations of fixation 1 (top) and fixation 2 (bottom) in Experiment 5.1 in relation to item positions, which are represented by grey circles.

In sum, the eye movement data may be interpreted so that fixations locations indicate the visual processing of the nearest search item, while acknowledging that eye movements not as accurate as this suggests.

Frequency of fixating the target (first two fixations). To investigate the efficiency of guidance towards the target in each condition, the mean frequency of each participant fixating near the target (see above) was calculated by summing the number of trials on which a target was fixated and then dividing this by the total number of trials, for each display type and fixation number. Data were pooled across target type, as in the RT analysis. The data were then adjusted for chance, so that the probability of a random fixation directed to a target was subtracted from the relevant frequencies at both fixations. This value was $^1/_9$ (there were nine search items) and was the same for fixation 1 and fixation 2. Fixations attributed to the same item (immediate re-fixations) were not removed as these may have occurred due to successive eye-movements being directed with increasing accuracy to the same stimuli (see above). Group means are shown in Figure 5.7.

A two-factor ANOVA (fixation number, display type) revealed a main effect of fixation number ($F(1,34)=71.1$, $p<0.001$, partial $\eta^2=0.67$), with the frequency of a target-fixation increasing from fixation 1 (adjusted probability of 0.041) to fixation 2 (adjusted frequency of 0.179). There was also a main effect of display type ($F(2,68)=7.6$, $p=0.001$, partial $\eta^2=0.183$). *A priori* comparisons across display type indicated a reduced likelihood of target-fixation when the distractor ratio was balanced compared to when a small orientation/large colour subset of distractors (a difference of 0.063, $p<0.001$) or a large orientation/small colour subset (a difference of 0.038, p=0.035) was displayed. No other comparisons or interactions reached significance.

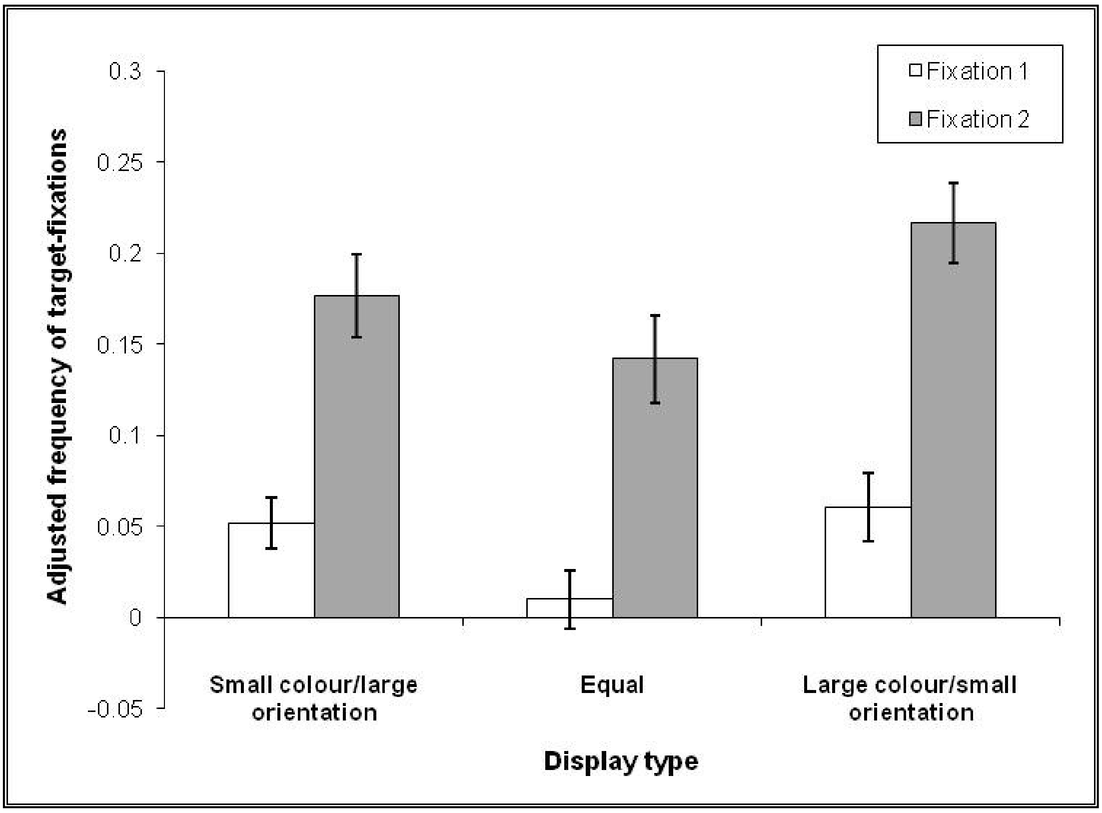

Figure 5.7. Means (+/- one standard deviation) of mean frequency of a fixation being directed to the target, adjusted for chance, from Experiment 5.1, split by display type (see Figure 5.1) and fixation number.

Frequency of fixating a distractor type (first two fixations). To analyse which distractor type was fixated, I removed trials where the target was fixated either on the first or second fixation to reduce the influence of target-fixations (see Shen et al., 2000). I then calculated the mean frequency of each fixation being directed to a distractor with the same colour as the target. As this probability covaried with the probability of fixating distractors with the same orientation as the target, this measure reflected the bias present between the two dimensions for each condition.

The resulting data were adjusted to control for chance fixation of the distractor in question. As trials with target-fixations within the first two eye movements had been removed, the probability of the target being fixated was zero. Therefore, to adjust the data I subtracted the probability of the stimulus being fixated at random, with the target ignored from the relevant probability. For example, the chance likelihood of the initial fixation directed to a distractor with the same colour as the target in a trial with a BH target and a 2BV, 6GH array (e.g., Small colour/large orientation condition) was $^2/_8$ (rather than $^2/_9$ if the target were considered). This figure was then subtracted from the relevant measured mean frequency. As a consequence, a measured frequency of zero indicated that the likelihood of a fixation directed to that distractor was no different from chance. Positive values indicate a bias towards stimulus sharing the colour with the target; negative values indicate a bias towards stimuli with the same orientation as the target. Group means are shown in Figure 5.8.

A two-factor ANOVA (fixation number, display type) demonstrated reliable main effects of display type ($F(2,68)=38.0$, $p<0.001$, partial $\eta^2=0.528$) and fixation number ($F(1,34)=5.354$, $p=0.027$, partial $\eta^2=0.136$). *A priori* comparisons indicated a strong bias towards fixating the smaller subset of distractors. The frequency of fixating a distractor sharing the same colour as the target was higher when a smaller colour group was displayed compared to when the ratio was balanced (a difference of 0.16, $p<0.001$). An opposite, negative bias (e.g., away from fixating distractors with the target-colour) was evident when there was a smaller orientation subset (a difference of -0.169, $p<0.001$) compared to when distractor numbers were balanced, indicating a preference towards fixating distractors matching the target in orientation.

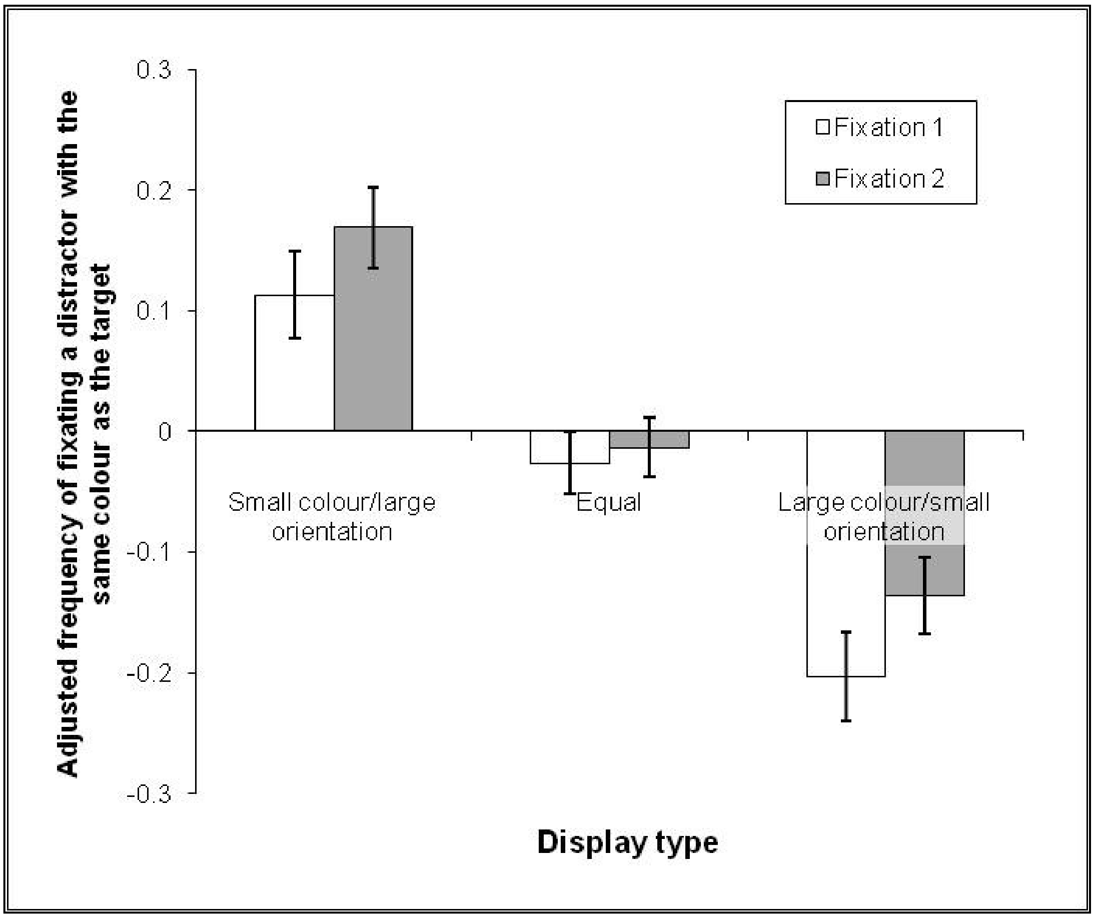

Figure 5.8. Means (+/- one standard deviation) of mean frequency (adjusted for chance) of a fixation being directed to a distractor with the same colour as the target in Experiment 5.1, split by display type (see Figure 5.1) and fixation number. As the types of distractor covary, positive means indicate a bias towards fixating distractors with the same colour as the target; negative means indicate a bias towards fixating distractors with the same orientation as the target.

The main effect of fixation number indicated an initial bias across display types towards fixating distractors with the same orientation as target (fixation 1: adjusted frequency of -0.038), was eliminated at fixation 2 (adjusted frequency of 0.007). Although there was no two-way interaction (F<1), the variation across affected the small-subset bias differently depending on the dimension defining the subset (see Figure 5.9). When there was a small colour subset, the bias towards fixating this subset was increased. When there was a small orientation subset, the bias towards fixating this subset was decreased. However, as the latter bias was reflected in negative values (e.g., away from distractors with the target-colour) both effects were reflected in an overall increase in fixations to distractor with the target-colour.

To directly compare this effect on the smaller subset bias, the data from trials with uneven ratios were analysed, however only absolute values were assessed (e.g., without regard to the sign). A display type x fixation number interaction was evident ($F(1,34)=4.665$, $p=0.038$, partial $\eta^2=0.121$), reflecting an increase from fixation 1 to 2 when the subset shared the target colour (0.056) and a decrease when the subset matched its orientation (-0.067, although neither variation across fixations reached significance, $ps>0.1$). Further to this, there was a trend towards a stronger initial bias towards smaller subset search when the subset was the same orientation as the target compared to when the two matched in colour (a difference of 0.09, $p=0.056$). No difference was evident at second fixation (a difference of 0.033, $p=0.425$).

5.1.4: Discussion

RTs were facilitated at extreme ratios of distractors compared with when there were equal numbers of distractors. That is, there was a distractor ratio effect, although reduced relative to previous experiments (e.g., Experiment 3.2). There was also a higher frequency of the first two fixations directed to a target in these trials, with this likelihood increasing as the trial progressed (from fixation 1 to fixation 2). The type of distractor fixated largely followed the data from Shen et al. (2000), with initial eye movements biased towards distractors that were in the minority (smaller-group search, Sobel & Cave, 2002). This effect occurred regardless of the dimension defining the smaller group, although there was a trend towards the bias being larger when the minority group matched the orientation of the target. The preference for smaller group search increased for the subsequent fixation only when the smaller subset of distractors matched the target's colour. When the smaller group shared the target-orientation, the initial bias towards fixating this subset was reduced at second fixations.

Although the eye movement data indicated that search was guided, at least initially, towards the smaller group of distractors, this was not reflected in RTs to the extent expected, e.g., with more efficient performance at uneven ratios (e.g., Anderson et al., 2010; Sobel & Cave, 2002). RTs measure multiple processes – search, detection and discrimination of the target followed by a response. It may be that the current ratio manipulation was not sufficient to affect overall performance but did bias eye movements towards smaller-groups of distractors. The difference in the displays presented between a small colour and equal colour subset was only two distractors (three versus five). In a previous experiment varying distractor ratios (Experiment 3.2) the smaller colour subset of distractors contained four fewer items than the comparative subset on a balanced display and an RT ratio effect was evident. In the current study, it is likely that the differences in distractor ratios were large enough to bias eye movement but not robust enough to be reflect in overall search speeds.

Although, a bias towards subset search is thought to be due to stimulus-driven effects (Sobel & Cave, 2002), the pattern of distractor-fixations observed here may be due to both bottom-up and top-down processes. Early eye movements are associated with stimulus-driven factors while later eye movements are more goal-driven (van Zoest, Donk, & Theeuwes, 2004). Initial fixations could be seen to be directed towards the smaller group of distractors. Irrespective of the target identity, this smaller subset differs in both colour and orientation from the other distractors (blue vertical vs. green horizontal bars). Information pertaining to the target may then be available at second fixation, directing search towards items matching it in colour. For example, when first fixations were to the smaller subset sharing the target's colour this bias was increased at second fixation. When the minority of distractors match the target in orientation, the initial bias towards this subset was reduced at fixation 2. This pattern suggests that the colour of the target may be coded prior to the second eye movement. Search either remains within the smaller group of stimuli matching this colour or switches to the alternative subset when the minority group only matches the target in orientation.

However, it is unlikely that the target colour was preferentially detected early in search to the colour of other items on all trials – it shares the same colour with some distractors. An alternative, if complementary, proposal is that the search display is preferentially grouped by colour (Kyle & Cave, 1999). From Figure 5.1, smaller colour groups were present at both extreme ratios – either containing the target (Small colour group) or not (Small orientation group) with the latter subset smaller and therefore more salient (Duncan & Humphreys, 1984). A trend was evident towards a stronger bias when the smaller group of distractors matched the orientation of the target – a colour-defined smaller subset would be smaller in this condition. Therefore, initial search would be directed to both minority colour groups, with a larger bias when the group did not include the target (it was smaller). Search would continue within this colour group at fixation 2 only if it matched the colour of the target. Fixations to the colour group not containing the target would be redirected to the other, larger colour group at subsequent fixations. The colour of the target would play a round in this proposal, but only by its presence of absence within the colour-grouped subsets. I suggest that grouping between distractors and the target within the colour domain play a strong role in guiding search when smaller distractor subsets are present.

When the size of distractor subsets was matched, moreover, there was no bias towards fixating stimuli sharing either the colour or orientation with the target (cf. Williams & Reingold, 2001), reflecting both the effect of the two-target methodology and the balancing of dimensional differences undertaken during piloting (e.g., Bacon & Egeth, 1997; see Experiment 2.4). Guidance towards fixating the target was also reduced in this condition, relative to trials in which extreme ratios were presented, with this further demonstrated in longer RTs. While segmentation based on colour or orientation was important in directing search with mixed ratios of distractors, this differential segmentation process was not present with even numbers of distractors randomly interspersed in the displays. In Experiment 5.2, I investigated the effect of manipulating the spatial relationship between distractor types while maintaining a balanced ratio. The results should offer insights into search patterns when feature-specific guidance from distractors is not present.

Experiment 5.2: Varying the Spatial Layout

5.2.1: Introduction

Experiment 5.1 demonstrated how the features of distractors guide search in the absence of target-specific bias; fixations were directed towards the more salient smaller subsets of stimuli, while there was no bias when subset size was equal. The higher salience of the subsets here reflect bottom-up processes (an increase in local featural differences), with target-specific biases reduced due to the two-target methodology – participants searched for two possible target, although only one was present on each trial. Second fixation may be also directed by early coding of target-colour. Experiment 5.2 examined the effects of spatial- rather than feature-grouping on search. Previous research has found conjunction search to be facilitated when the target was surrounded by homogenous compared to heterogeneous distractors (Poisson & Wilkinson, 1992; Treisman, 1982). This could be due to two factors. First, there can be grouping based on the feature shared by local neighbours. This might guide attention into a group of items where the target differs from the other stimuli in terms of some local disparity. Second, the strength of any local disparity should be increased when the distractors have common features (e.g., colour or orientation) differing from the critical feature in a target. This disparity could enhance guidance to the target. These two possibilities were assessed here by measuring eye movements during search. If there is guidance by the grouped items, then eye movements may go to grouped members and this may even increase over time if grouping is relatively slow (emerging on second fixations more than first fixations). In contrast, effects of guidance by disparity should lead to eye movements to targets but not to grouped distractors.

Three display conditions were introduced: two where the distractors adjacent to the target were the same type, either differing from the target in either colour or orientation (cf. Kim & Cave, 1999) and one where distractor type alternated between across the search array (cf. Findlay et al*.,* 2001). I expected search efficiency to decrease in the latter, heterogeneous condition, both in terms of RTs and errors and in terms of there being a reduced frequency of fixations to the target in the first two fixations. However, the guidance available from spatially adjacent distractors in locally homogeneous trials, and the consequential disparity with the target, was also assessed so as to provide further insight into how stimulus-driven biases affect visual search.

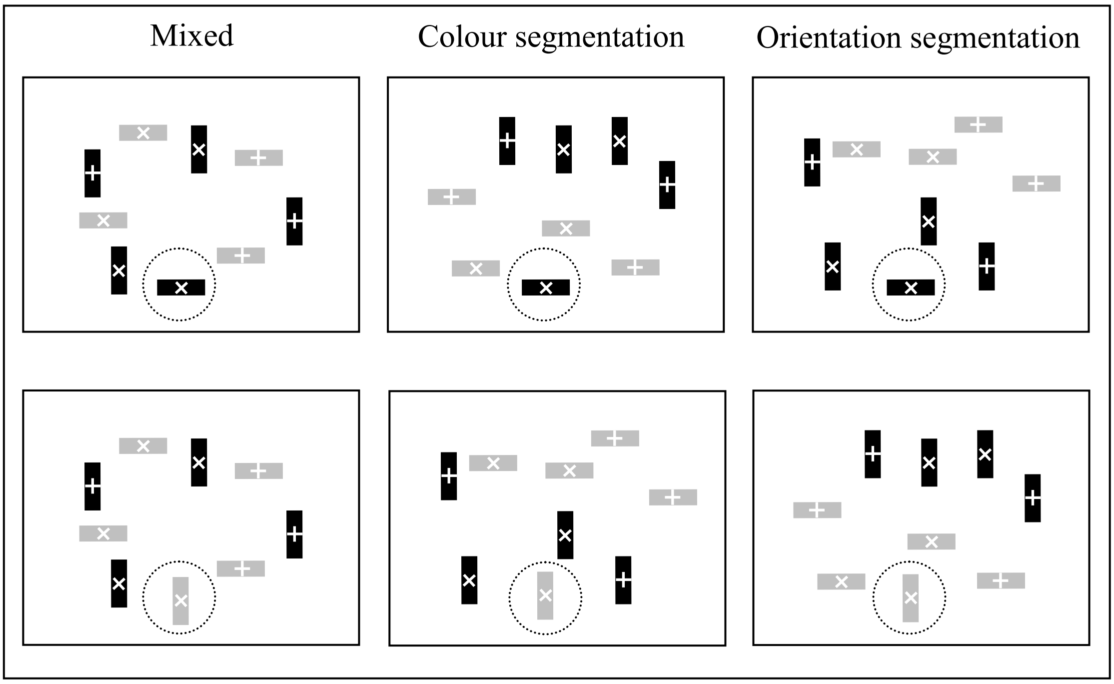

Figure 5.9. Examples of the three display types used in Experiment 5.2. In the Mixed condition, adjacent distractor alternated in type; in the Colour segmentation condition, the target was segmented by its local colour within a set of neighbours with the same orientation; in the Orientation segmentation condition, the target was segmented locally by its orientation within a group of items sharing its colour.

5.2.2: Method

The method was the same as Experiment 5.1, except for the points outlined.

Participants. Twenty-one students from the University of Birmingham took part, aged 18-30 (average 22.05), with 14 females, seven males. One participant was removed due to response accuracy of less than 90%.

Design. There were two main independent variables: display type (see Procedure section) and target type (blue horizontal, green vertical).

Procedure. There was one block of 120 trials with the number of practice trials varying between eight and 32. As in the Equal ratio condition from Experiment 5.1, there were equal numbers of each type of distractor. On Mixed trials, adjacent distractors alternated between the two types of stimuli (four blue vertical, BV, four green horizontal bars, GH); on Colour segmentation trials target-adjacent distractors shared its orientation but differed in colour to the target (e.g., a BH target surrounded by GH distractors); while on Orientation segmentation trials, the distractors adjacent to the target shared its colour but differed in orientation (e.g., a BH target would be surrounded by BV distractors; see Figure 5.9 for details). In the latter two conditions, to avoid difficulties in detecting a target at the edge of a homogeneous group (cf. Treisman, 1982) the target was always flanked by two stimuli of the same distractor type. To mask the manipulations, display type varied randomly trial-on-trial, with Mixed displays presented on half the trials while the remaining trials were equally split between Colour and Colour segmentation display types.

5.2.3: Results

RTs. The data were cleaned as previously and then separated by display type (see Figure 5.9). Median RTs in each condition for each participant were calculated, with group means shown in Figure 5.10. A one-factor ANOVA (display type) revealed a significant main effect ($F(2,38)=20.2$, $p<0.001$, partial $\eta^2=0.516$). RTs in the Mixed condition were longer than those in both the Colour and Orientation segmentation conditions (differences of 423ms, $p<0.001$, and 234ms, $p=0.001$). Comparing the two homogeneous conditions, there was a trend towards shorter RTs when target and local distractors differed by orientation compared when they differed in colour (a difference of 189ms, $p=0.082$).

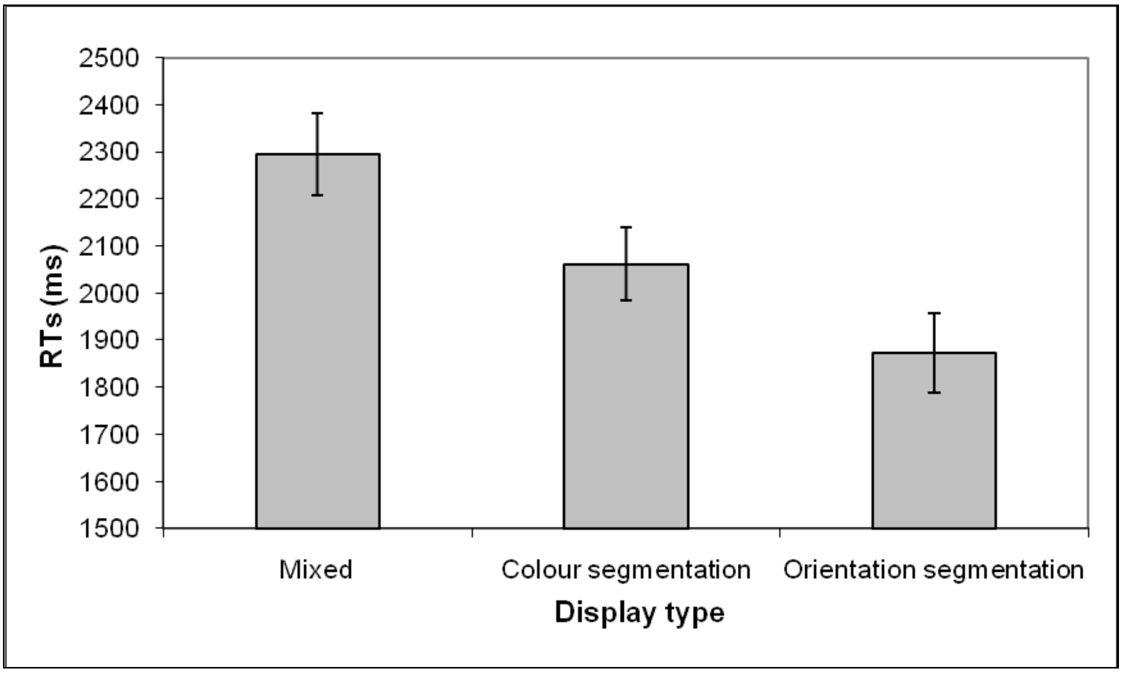

Figure 5.10. Means (+/- one standard error) of median reaction times (RTs), separated by display type (see Figure 5.9).

Fixations. The eye movement data were cleaned and the positions of first and second fixations determined as previously. The results were pooled across target type, with trials coded as per Figure 5.9. The data from one participant were excluded due to inaccurate responses (see RT analysis) and the results from a further participant were eliminated as a consequence of technical problems recording eye-tracking data.

Frequency of fixating the target (first two fixations). As previously, the nearest item to each of the first two fixations was assessed[6]. The mean frequencies of whether a fixation was directed to a target were then calculated for participants in each display condition. The data were again adjusted for chance (see Equal ratio condition, Experiment 5.1) and were split by display type (see Figure 5.9) and fixation number. Group means are shown in Figure 5.11.

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[6] Fixation-item differences did not differ to those outlined in Experiment 5.1.

A two-factor ANOVA (fixation number, display type) found a main effect of fixation number ($F(1,18)=48.7$, $p<0.001$, partial $\eta^2=0.73$); there was a higher frequency of second fixations being directed towards the target (adjusted frequency of 0.106) compared to initial fixations (adjusted frequency of 0.018). There was also a main effect of display type ($F(2,36)=4.1$, $p=0.024$, partial $\eta^2=0.187$).

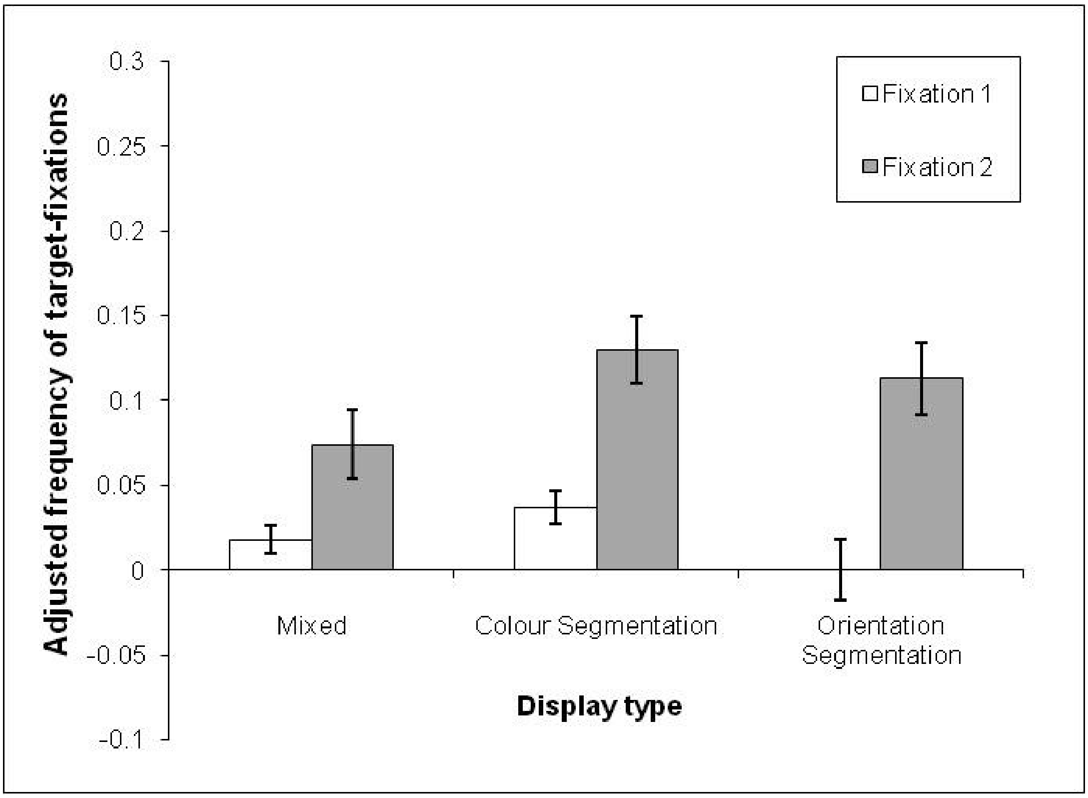

Figure 5.11. Mean (+/- one standard deviation) of mean frequency (adjusted for chance) of a fixation directed to the target from Experiment 5.2, split by display type (see Figure 5.9) and fixation number.

The target-fixation frequency was higher when the homogenous group of distractors differed in colour to the target compared to when distractor types alternated (Colour segmentation vs. Mixed condition, a difference of 0.038, $p=0.01$) or the target and distractors differed in orientation, although the latter difference was only borderline significant (Colour vs. Orientation segmentation, difference of 0.027, $p=0.068$). The fixation number x display type interaction did not reach significance

(F(2,36)=1.7, p=0.205, partial η^2=0.084), although there was a trend towards a greater frequency of initial target-fixations (e.g., at fixation 1) in the Colour relative to the Orientation segmentation condition (t(19)=2, p=0.066, two-tailed; see Figure 5.11). Following this, the frequency of first fixations to the target when it differed from adjacent stimuli in colour was significantly above chance (t(18)=3.668, p=0.002; one-tailed).

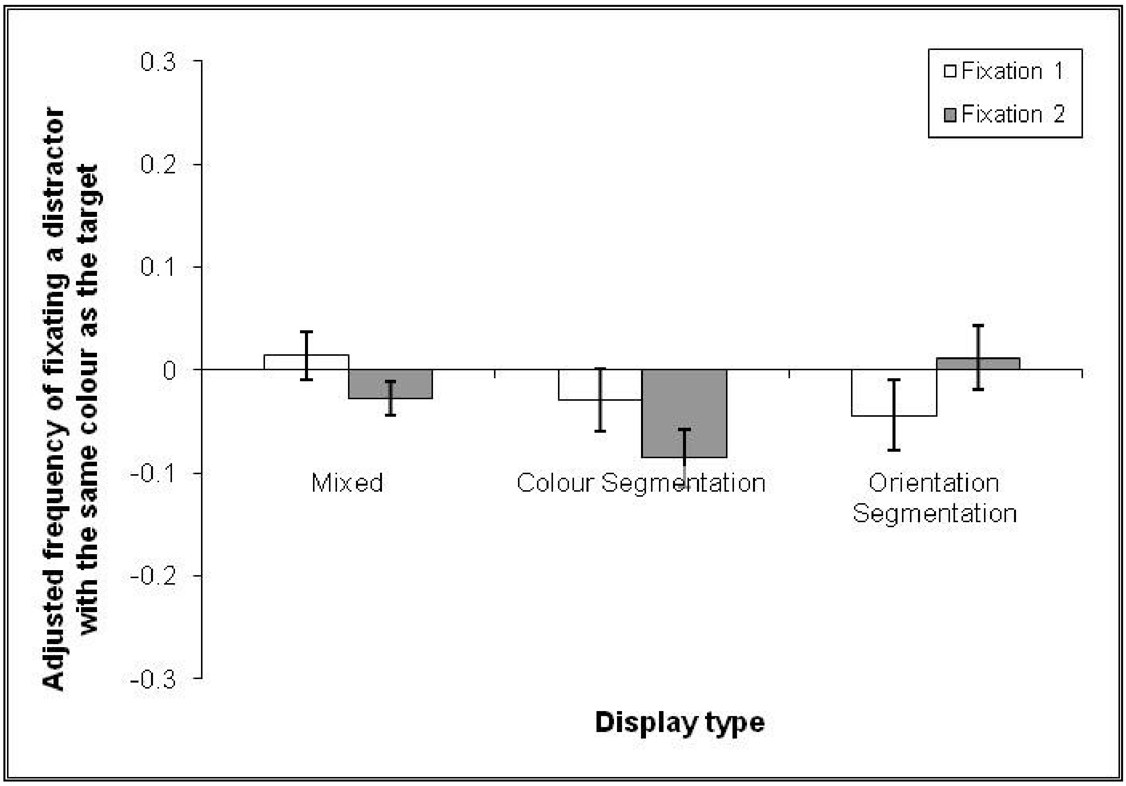

Figure 5.12. Means (+/- one standard error) of the mean frequency (adjusted for chance) of a fixating being directed to a distractor with the same colour/orientation as the target in Experiment 5.2, split by display type (see Figure 5.9) and fixation number. Positive means indicate more fixations to distractors with the same colour as the target; negative means indicate a bias towards fixating a distractor with the same orientation as the target.

Frequency of fixating a distractor type (first two fixations). As previously, trials with either the first or second fixation directed to the target were removed, with the resultant data used to calculate the mean frequency of fixating a distractor with the same colour as the target. The data was adjusted to control for chance (see Experiment 5.1), so zero indicated no bias towards fixating either type of distractor. Positive means reflected a bias towards fixating a distractor with the same colour as the target while negative means indicated a bias towards fixating a distractor with the same orientation as the target. The data were separated by fixation number and display type. Group means are shown in Figure 5.12.

A two-factor ANOVA (fixation number, display type) showed a significant interaction (F(2,36)=3.3, p=0.05, partial η^2=0.15), reflecting differing bias across fixation depending on the display type. Analysing data from homogeneous displays, there was a borderline significant fixation number x display type interaction (F(1,18)=4.4, p=0.051, partial η^2=0.196). At fixation 2, there was trend towards a stronger bias toward distractors sharing target-orientation on Colour segmentation displays (a difference of 0.096, p=0.058), while there was no such difference for initial eye movements (a difference of 0.015, p=0.732, partial η^2=0.116). There was no difference across fixations when displays were Mixed (F(1,18)=2.4, p=0.142, partial η^2=0.116). T-tests indicated there was a significant bias (e.g., the value differed from zero) towards the second fixation being directed to distractors matching the target in orientation when they differed from the target in colour and were adjacent to the target (Colour segmentation condition, t(18)=-2.971, p=0.008; one-tailed). No similar bias was evident in the Orientation segmentation condition (t(18)=0.383, p=0.706; one-tailed).

5.2.4: Discussion

As in previous research (e.g., Poisson & Wilkinson, 1992), search was facilitated when targets were surrounded by homogeneous compared to heterogeneous distractors. However, the size of this facilitation effect was partially modulated by the target-distractor relationship within these homogeneous groups; there was a trend towards shorter RTs when the adjacent stimuli differed in terms of their orientation disparity (and shared the same colour) compared to when they differed in terms of their local colour disparity (and possessed the same orientation). Poisson and Wilkinson proposed that the target and adjacent stimuli were processed as a unit, with a local pop-out search facilitating search. Indeed, the increase in efficiency between the Mixed and the two Grouped conditions could be explained due to the target 'popping-out' from the surrounding identical distractors. However, any differences between the Colour and Orientation segmentation conditions are unlikely to be the consequence of differences between colour- and orientation-defined search per se, as search efficiency along each dimension was equated in pilot work (cf. Bacon & Egeth, 1997). Instead, the difference may reflect the ease of local segmentation or differences in colour and orientation grouping.

Any distinction between segmentation and grouping cannot be made from the RT analysis. However, the two can be separated following the eye movement analysis: fixations towards specific distractors could be seen to reflect a bias in grouping in that display type while an increase in the likelihood of fixating the target may indicate better segmentation. Data on target fixations indicated there was increased guidance towards targets at first fixation when there was a colour disparity between target and adjacent distractors compared to when stimuli were heterogeneous (Mixed condition); there was also a higher frequency of target-fixations (especially at fixation 1) when the target and neighbouring distractors differed in colour compared to when there was a local orientation disparity.

Analysis of the type of distractors fixated also suggests early guidance from target colour. When there was a colour disparity between target and adjacent distractors (Colour segmentation displays), second fixations were biased towards distractors sharing the target's orientation, stimuli that were adjacent to the target. The local colour disparity may be detected at fixation 1 (either overtly or covertly, see 1.2.2 for details). Second fixations may then be directed towards the spatial co-ordinates of the target, with mislocalised eye movements directed to the adjacent subset of items – which share the same orientation as the target. Alternatively, following the early detection of the colour of the target, it may be that orientation-based grouping followed at second fixation (cf. Hodsoll & Humphreys (2007), directing search to distractors sharing the target's orientation.

The strength of this colour signal, however, was not reflected in search efficiency. Indeed, search was quicker when the target differed in orientation to surrounding distractors. Despite this RT advantage there were fewer target-fixations, relative to when target and local distractors differed in colour, and fixations were equally likely to go the group of items containing the target compared to that not including the target. Both these factors suggest that with no guidance from distractors that the orientation signal was too weak to direct initial search processes. Following Experiment 5.1, it may be that the improvement in overall performance in the Orientation segmentation condition (e.g., shorter RTs) was due to stronger grouping between stimuli matched in colour compared to grouping by orientation (cf., Kim & Cave, 1999). Search would then be efficiently directed either to colour-defined subset, as indicated by the lack of a bias at second fixation (see Figure 5.12). If the target was in this group, the local orientation disparity between target and distractors within this subset would guide search (cf. Friedman-Hill & Wolfe, 1995). If the group did not contain the target, search could then be speedily redirected. This suggests that when the target signal is strong (e.g., a local colour difference), search is directed towards its local. When this signal is weak (e.g., a local orientation difference), grouping processes between stimuli may play a stronger role.

Eye movements to distractors in the Mixed condition, on the other hand, showed no initial bias towards fixating distractors sharing either colour or orientation with the target, and this lack of guidance was also apparent in the reduced likelihood of the target being fixated and longer RTs. The absence of differences between distractors sharing the target's colour and its orientation fits with the colour and orientation signals being matched (in the absence of grouping).

5.3: General Discussion

Two experiments examined the effects of the featural and spatial relationships between distractors on search and eye-tracking behaviour during a conjunction search. Participants searched for two possible targets, so that target-specific guidance processes were minimized while any bottom-up dimensional biases were matched during piloting[7]. Experiment 5.1 showed strong guidance towards searching smaller subsets of distractors, regardless of the defining dimension. Compared to when there were equal numbers of distractors, search was facilitated at extreme ratios (a ratio effect, cf. Sobel & Cave, 2002), with corresponding increases target-fixations. Following Shen et al. (2000), fixations to distractors were initially biased towards stimuli in smaller subsets. While the bias increased at fixation 2 when the smaller group of distractors matched the target, a decrease was evident when the subset matched the target's orientation. This suggests that small-group-specific bias occurs

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[7] See Experiment 2.4.

early in search. No bias was present, however, when the distractor ratio was balanced indicating top-down and bottom-up guidance of search towards stimuli with the same colour or orientation with the target was matched.

Experiment 5.2 compared guidance during heterogeneous and homogenous displays, with the latter display type split by whether the target and its adjacent stimuli differed in colour (they were grouped by orientation) or orientation (grouped by colour). In the absence of *a priori* knowledge about the target-identity or guidance from a subset of distractors (see Experiment 5.1), initial fixations were directed towards the target when it differed in colour to adjacent distractors. Second fixations not to the target were biased towards stimuli adjacent to the target which differed in colour yet shared their orientation with the target. This suggests that the colour disparity may direct search to the location of the target and that less accurate fixations were to stimuli surrounding this location. No such bias was evident on distractor-fixations when there was a local orientation disparity, with fixations to the target also reduced in this condition.

There was a trend towards overall RTs being faster in the Orientation segmentation condition than the Colour segmentation condition. This could occur if target detection was determined by the segmentation of the target from the grouped distractors, which would therefore be stronger in the orientation than the colour domain here. However, this goes against the pattern of fixations outlined above. It may be that the grouping from the colour feature shared by the target and adjacent distractor group (they differed in orientation) in this condition offered a benefit to overall performance, rather than just the first two fixations, compared to when the target and neighbouring stimuli shared the same orientation (where they differed in colour).

5.3.1: Target or distractor colour

In both experiments, the data suggest that the colour of the target is detected early in search. When the spatial relationship between target and local distractors was manipulated (Experiment 5.2), initial eye movements were directed towards the target when there was a local colour difference. Fixations to distractors were then biased towards the search items adjacent to the target, which also shared its orientation. The detection of the colour disparity between target and distractors may therefore bias search spatially, indicating the location of the subset of distractors contained the target.

On trials where the distractor ratio was manipulated but adjacent items were allocated randomly (Experiment 5.1), initial fixations were directed towards the distractor type in the minority, while the item fixated second was influenced by the colour of the target rather than the nature of the distractors present. Two proposals explain this data. During the initial bias towards the minority subset, the colour of the target may be detected and subsequent search is then directed towards stimuli matching this colour. On the other hand, search items may be initially grouped by colour. In this case, on trials where the distractor ratio was uneven, smaller colour groups are present, whether this colour is shared with the target (Small colour group) or not (Small orientation group). When the minority colour group includes the target, the initial bias increases at second fixation. When it does not, a strong initial bias decreases at fixation 2.

Evidence from Experiment 5.2 suggests that in certain conditions target-colour can be coded at first fixation, which may also occur when distractors are randomly distributed (as in Experiment 5.1). Indeed, on displays with uneven distractor ratios, the target is more likely to differ from adjacent distractors (see Figure 5.1), suggesting that target-colour, if detected, can guide search early on in the search process. It may be, however, that these target-specific processes operate in conjunction with strong grouping by stimuli sharing the same colour. If search items are grouped preferentially by colour, on displays with uneven distractor ratios a strong local colour signal would direct search towards the minority colour-defined groups. Whether this signal coincides with the colour information from the target depends on the display. If it did not, search would be redirected accordingly.

In summary, the data suggest that when guidance from distractors is available, first fixations are strongly guided to a minority colour-defined group. Target-colour may play a role later in search, guiding search towards stimuli matching target in colour (e.g., Williams, 1966). In the absence of direction from distractor, early search may be directed by a local colour disparity towards the location of the target.

5.3.2: Theoretical models

Guided Search Theory (GST: Wolfe, 1994; Wolfe et al., 1989) proposes an initial preattentive parallel stage of visual processing where basic features – such as colour and orientation – are coded independently in separate retinotopic feature maps. The activation within each feature map reflects both the bottom-up saliency of the stimuli (e.g., dependent on local differences between elements) and top-down processes (pre-activation of the maps by prior knowledge about the target). These measures are summed into a saliency map where a second level of processing guides attention to locations based on the level of activation. Within this model, the two-target methodology used in our current research should remove, or at least reduce, top-down processes biasing the activation of array stimuli, as participants have no knowledge of which target will be present on each trial. Further to this, the search items all share either colour or orientation with one of the possible targets so that attention would initially be guided by stimulus-driven processes with top-down, task-specific direction only available when target identity had been detected.

Our data indicate that, in the absence of a target-specific bias, stimuli in a smaller colour subsets guide attention more efficiently than a minority group of stimuli with the same orientation. Later top-down effects from target-colour were evident when the strength of the local disparity was not consistent. Target-specific bias was available initially, but only when the target differed locally with adjacent distractors. These dimensional asymmetries were present despite the balancing of colour- and orientation-defined singleton search with the same search stimuli. To bring GST into line with our findings, the activation output from the particular feature maps of stimuli with the same colour value should be weighted more than the complementary activations for stimuli sharing the same orientation, thereby guiding attention preferentially to locations grouped by the same colour, especially when adjacent to stimuli with opposite colour values. A simpler, different account of the data can be formulated in terms of Attentional Engagement Theory (AET, Duncan & Humphreys, 1989, 1992). AET is a two-stage model in which preattentive grouping of stimuli is followed by a competitive matching of grouped representations to a template of the target. For this account, there would be two target-templates with no initial competitive bias bestowed on any stimuli. However, in order to fit our data, an increase in weighting would be allocated to search items with the same colour, therefore offering a competitive advantage relative to other items. This would allow a colour-defined group to be rejected together, or increase the likelihood of stimuli within the group to gain access to the visual sort term memory.

5.3.3: Conclusion

These results should be interpreted with certain caution, considering the spatial accuracy of the eye-tracking set-up as outlined previously. Further to this, attributing the nearest item to a specific eye movement, particularly at first fixation, may be misguided, as the distance between the fixation-location and item is not optimal, suggesting search may be directed to the geometric centre of the stimuli (cf. Zelinsky et al., 1997). While these fixation-item distances were not ideal, they were within the penumbra of the stimuli (closer than half the average distance between adjacent items). The spatial accuracy of fixations does improve, with second fixations close to the search items, indicating that the method of eye-tracking was sensitive to the improved guidance during search.

With these caveats, I feel I present robust evidence for stronger initial effects on search from smaller groups sharing the same colour, relative to those sharing the same orientation. Target-colour, once detected, may bias search later in the search process.

CHAPTER 6

Conjunction Search with Top-Down Cueing: an Eye Movement Study

6.0.1: Abstract

Four experiments examine the effect of prior knowledge about the target on reaction times (RTs) and eye-movements during conjunction search. Pre-cues were used to indicate either the likely colour or orientation of a target, with this information correct on 80% of trials. Cueing effects were isolated by comparing performance with a baseline condition where no target-specific information was evident (see Chapter 5). In Experiment 6.1 the effects of colour and orientation cues interacted with the number of stimuli sharing the cued feature. While colour cues facilitated the parsing of stimuli into groups, orientation cues guided attention by enhancing the local orientation disparity within colour-defined subsets. These effects were evident following both stimulus and verbal cues, and increased with longer cue durations (Experiment 6.2). Experiment 6.3 used trials where distractors adjacent to the target were either homogenous or heterogeneous, with the results indicating that the effects of colour cues occur at a global level while orientation cues only guides search at a local level.

6.0.2: Introduction

Searching the visual world is a complicated process, as typically there may be many objects competing for both our overt attention (where we move our eyes) and covert attention (which objects are selected for further processing; see 1.2.2). The efficiency with which we detect a search target, such as a car in a parking lot, is affected by our prior knowledge, such as knowing its colour or make. If this knowledge is correct, the target may be found quickly, while the process may be slowed by incorrect information. Previous research (Anderson, Heinke, & Humphreys, 2010; Müller, Riemann, & Krummenacher, 2003) has shown that giving participants knowledge of the colour of a target prior to a search task results in a larger modulation in reaction times (RTs) compared to when participants are given foreknowledge of the target's orientation (see Chapters 3 and 4). The above data suggest that the advantage reflects differential top-down effects of colour compared with orientation on search. The mechanisms which determine the top-down colour advantage remain unclear, however. The current study sets out to investigate this by measuring eye movements as well as RTs and errors, to assess effects of cueing colour and orientation on overt as well as covert search mechanisms.

Although the vast majority of studies of search have used only RT and error measures, an increasing number have recorded eye movements to gain a finer-grained analysis of how search operates (e.g., Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006; Rutishauser & Koch, 2007; Shen, Reingold, & Pomplun, 2000; Williams & Reingold, 2001). These studies have assessed both efficient search (e.g., where the target differs from distractors on the basis of a single features) and inefficient (serial) search (e.g., where targets and distractors differ in a conjunction of features; e.g., Findlay et al., 2001; Shen, et al., 2000; Williams & Reingold, 2001). The last studies are particularly relevant here as I use conjunction search tasks.

Data on eye movements in conjunction search indicate that saccades tend to be made to stimuli sharing their features with target. For example, inaccurate fixations (on distractors rather than targets) typically fall on distractors whose features overlap those of targets (e.g., Findlay, 1997; Findlay et al., 2001; Shen et al., 2000; Williams & Reingold, 2001). Findlay and colleagues (Findlay, 1997; Findlay et al., 2001) measured eye movements during a search for a conjunction of colour (red or green) and shape (cross or circle), with participants instructed to make a speeded eye movement towards the target. The arrays were in two concentric circles with adjacent stimuli alternating in colour. Eye movements were found to be directed towards stimuli with either the target colour or target shape, and not to stimuli in the same circle or at a particular eccentricity. This pattern of featural-guidance has been found to be affected by the nature of the visual array. The relative ratio of different coloured distractors influences the guidance of eye movements to a target. RT data show that search is facilitated at extreme distractor ratios (Bacon & Egeth, 1997; Egeth, Vrizi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Soto & Cave, 2002), suggesting that stimulus-driven segmentation processes bias participants towards the smaller subset of distractors. This can occur regardless of the dimension defining this group of stimuli (Soble & Cave, 2002). Eye movement data show a similar preference (Shen et al., 2000).

As well as the ratio between distractors, the discriminability of stimuli within the relevant dimension has been show to affect search. Colour differences, in particular, have been shown to be critical (see 1.5.4). More recent studies have shown stronger guidance remains for colour when dimensional differences in salience were balanced (see 1.5.4). Moreover, stronger guidance from colour has also been shown when investigating how information presented prior to search effects eye movements. However, few studies had separated stimulus-driven and top-down biases until Anderson et al. (2010; see Chapter 3). From their data, Anderson et al. proposed that colour cues facilitated the segmentation of the displays into colour groups more rapidly than orientation cues facilitated the segmentation of the displays into orientation groups, enabling search to be initiated more rapidly in the appropriate (cued) colour groups.

In the present study, I pitted the effects of cueing against the bias from smaller-subset search (cf. Sobel & Cave, 2002) to assess the interaction between these factors and how they develop during search. All tasks involved search for either a blue horizontal or green vertical bar target, with blue vertical and green horizontal bar distractors. During pilot studies, I adjusted the colours of the stimuli to balance search for a colour- and orientation-defined target (see Chapter 2 for further details). Prior to each search, a cue was presented whose featural information either matched (on 80% of the trials) or did not match the colour or orientation of the target in the following array (on 20% of the trials). These cueing effects were compared to performance in a separate block of neutral uncued trials, where no cue was presented[8]. In Experiment 6.1, I measured the effect of a visual cue presented for 200ms, varying the ratio of the two types of distractor (either 1:3, 1:1, or 3:1). Manipulation of the distractor ratio should differentially cue attention to the minority distractor group in a bottom-up manner (see Sobel & Cave, 2002). Subsequently, I compared attentional guidance when visual and verbal cues were presented for longer durations (1200ms, Experiment 6.2). Experiment 6.3 examined the effects of cueing when the spatial relationship between distractors was controlled but the distractor ratio was balanced.

Experiment 6.1: Varying the Distractor Ratio with Visual Cues

6.1.1: Introduction

Anderson et al. (2010) show that colour cues are more effective than orientation cues in directing attention to targets in colour-orientation search tasks. Experiment 6.1 here set out to replicate this whilst also recording participants' eye

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[8] Details are outlined in Chapter 5.

movements. By measuring eye movements, important new information can be captured concerning the search processes, as data are acquired about the evolution of search over time and not just how long is finally taken to find a target. For example, data can be provided on whether cueing directs the first eye movement to a target or to a distractor matching the cued feature and/or whether the cue leads to gaze being held on matching distractors when fixation falls there. From this, converging evidence is gleaned on whether the top-down cue influences the first stages of selection or the disengagement of attention following selection. By combining cueing with a manipulation of the distractor ratio, the experiment also assesses whether the distractor ratio alters selection or disengagement processes, and how top-down cueing combines with bottom-up segmentation to guide visual search.

6.1.2: Method

The trials outlined were undertaken in the same experimental sessions as the neutral, uncued trials outlined in Experiment 5.1[9]. The method was largely the same as in the previous study with exceptions outlined below.

Participants. Nineteen University of Birmingham students, one male, 18 female, aged 18-21 (average 18.89) took part.

Design. There were four main independent variables: distractor ratio (see Figure 6.1), cue validity (valid, neutral, invalid), cue dimension (colour, orientation), and target type (blue horizontal, green vertical).

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[9] Half the participants tested in Experiment 5.1 were randomly assigned to take part in Experiment 6.1 while the others took part in Experiment 6.2.

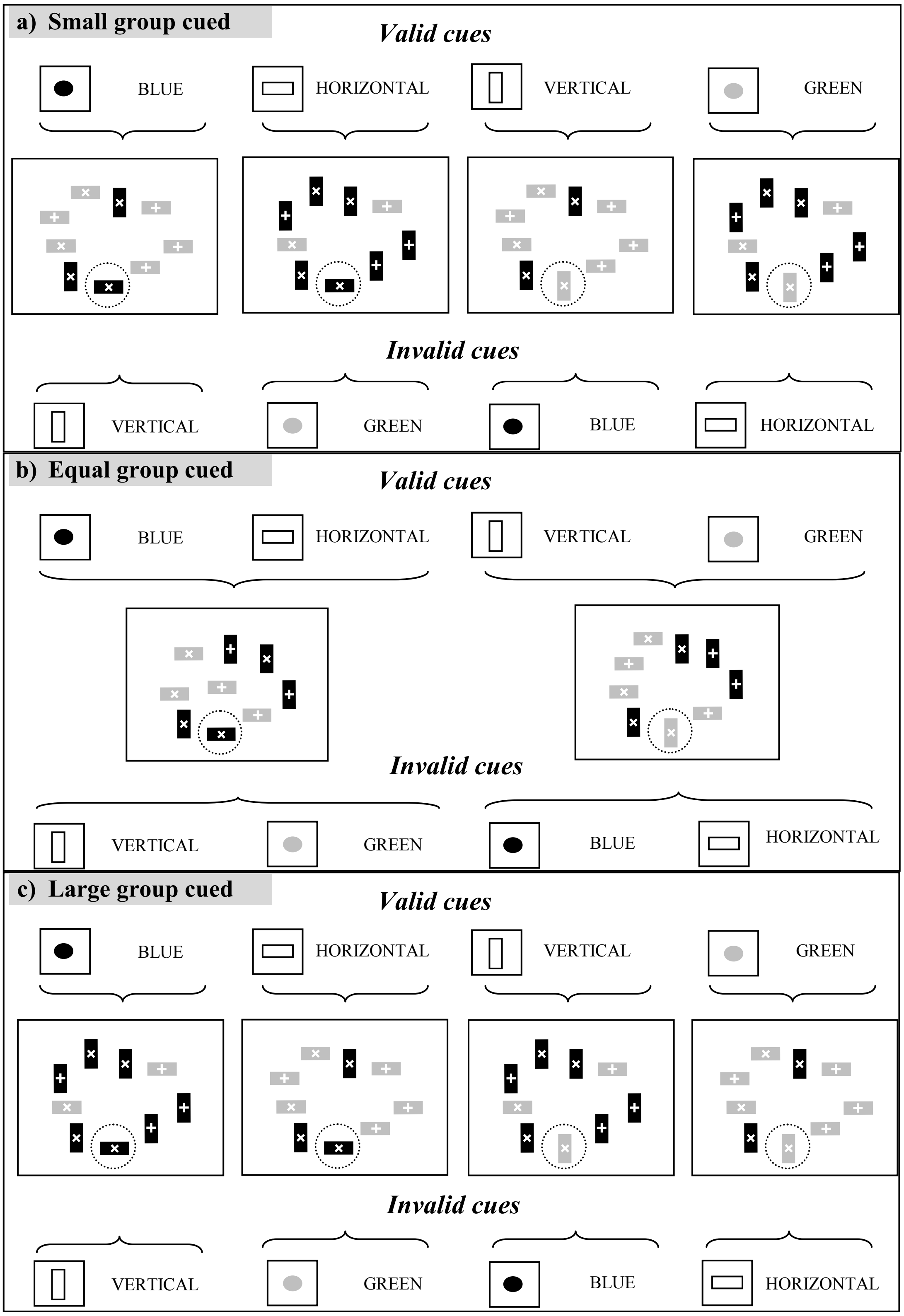

Figure 6.1. Illustration of the how the distractor ratios used in Experiment 6.1 were coded, depending on the number of stimuli matching the cue stimulus. Blue stimuli are shown in black, green in grey, light grey symbols and light background in white.

Stimuli. One of four cueing stimuli were used: a blue patch or a green patch (cueing the colour of the target), or a white horizontal or a white vertical bar (orientation cues). The colour levels for the patches (coloured circles with diameters of 0.8cm, 0.8°) matched the levels those of the search items, while orientation cues possessed the same dimensions as array stimuli, but were white with black edges to improve visibility against the grey background.

Procedure. Contrary to Experiment 5.1, prior to the search array a visual stimulus was presented whose colour or orientation was likely to match the following target. Participants were informed that when the cue was a green or blue coloured patch the target was likely to be that colour. They were also told that when the cue was a white line, the target was likely to have the same orientation. All cues matched the target 80% of the time while the target was the other colour or orientation on the remaining 20% of trials, with participants informed of this probability. There were 30-40 practice trials, followed by two blocks of 120 trials.

The methodology of the neutral trials used as a baseline condition in this study (see Experiment 5.1 for details), with trials presented in a separate block. The time until participants' response was recorded (RTs), along with the accuracy of the response.

6.1.3: Results

RTs. Trials that were inaccurate were removed, the data cleaned as previously and median RTs in each condition for each participant were calculated. Distractor ratios were re-categorised depending on the cue. Trials where the cued feature matched that defining the smaller distractor subset were coded as the Small cued group (see Figure 6.1a), while trials with the cue feature matching that shared by the larger distractor subset were included in the Large cued group condition (see Figure 6.1c). Trials with 50:50 ratios were labelled as the Equal cued condition (see Figure 6.1b). Data were averaged across target type due to low numbers of trials in the invalid condition and for parsimony only the effects of cueing were analysed.

RT Cost-Benefits. The relative effects of cueing by colour and by orientation were examined by subtracting median RTs in each cueing condition with corresponding data from neutral trials[10]. The cueing conditions were defined according to the assumed attribute of the target that would be used to guide attention, and the distractor ratios for Small and Large group cued conditions are shown in Figure 6.1. Neutral conditions with displays matching those presented in the cued trials were therefore used to calculate RT Benefit/Cost. Mean RT Benefits/Costs are shown in Figure 6.2.

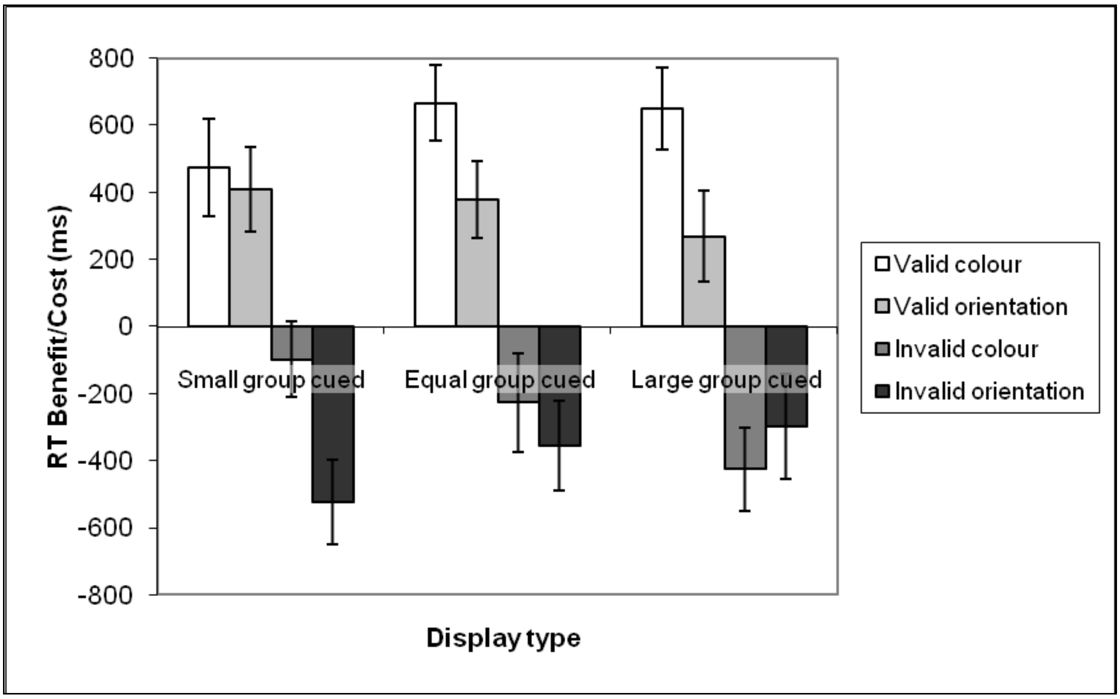

Figure 6.2. Means (+/- one standard error) of RT Benefits/Costs from Experiment 6.1, separated by display type, cue dimension and cue validity. See Figure 6.1 for details of display type coding.

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[10] For details of the uncued, neutral condition see Chapter 5.

A three-factor ANOVA (display type, cue dimension, cue validity) revealed a main effect of validity (F(1,17)=58.7, $p<0.001$, partial $\eta^2=0.775$) and a significant three-way interaction (F(2,34)=8.7, $p=0.004$, partial $\eta^2=0.338$). There were differential effects of cue validity and cue dimension depending on the size of group being cued, so separate analyses for each display type were undertaken. Analysis of the Small group cued condition showed a main effect of validity (F(1,17)=16.5, $p=0.001$, partial $\eta^2=0.338$) and cue dimension (F(1,17)=36.4, $p<0.001$, partial $\eta^2=0.682$). There was also a borderline significant interaction (F(1,17)=4, $p=0.063$, partial $\eta^2=0.189$), with larger cost from invalid orientation compared to invalid colour cueing (a difference of 426ms, $p<0.001$). There was no such difference in the effect of valid cues across the different cue dimensions (a difference of 64ms, $p=0.594$).

Analysis of data from trials with the Equal group cued showed only main effects of validity (F(1,17)=82.6, $p<0.001$, partial $\eta^2=0.829$) and cue dimension (F(1,17)=14.9, $p=0.001$, partial $\eta^2=0.467$). There was a benefit from valid cues (522ms) and a cost from invalid cues (-292ms). The benefit from valid colour was stronger than the cost from invalid colour cues (220ms) while the combined effect of cue validity (reflecting the difference between valid and invalid trials) was more balanced following orientation cues (11ms). However, the effect of cue validity was matched across cue dimension (cue validity x cue dimension; F(1,17)=1.5, $p=0.242$, partial $\eta^2=0.08$).

For the Large group cued condition, there was a main effect of validity (F(1,17)= 46.1, $p=0.001$, partial $\eta^2=0.731$), a borderline significant effect of dimension (F(1,17)= 4.2, $p=0.057$, partial $\eta^2=0.197$) and a reliable cue validity x cue dimension interaction (F(1,17)= 12.3, $p=0.003$, partial $\eta^2=0.42$). There was a significantly larger benefit from valid colour cueing than from valid orientation cueing (a difference of 381ms, p=0.002). There was a numerically larger cost from invalid colour cueing compared with invalid orientation cueing but this difference was not reliable (a difference of 126ms, p=0.163).

Exp.	**Cue**	**Display type**			
		Small group cued	**Equal group cued**		**Large group cued**
6.1	Valid colour	95	98		97
	Invalid colour	98	99		97
	Valid orientation	98	95		96
	Invalid orientation	96	97		98
			Cue type		
			Visual cue	**Verbal cue**	
6.2	Valid colour		95	96	
	Invalid colour		98	97	
	Valid orientation		96	96	
	Invalid orientation		96	95	
		Mixed	**Colour segmentation**		**Orientation segmentation**
6.3	Valid colour	97	99		98
	Invalid colour	98	90		91
	Valid orientation	99	98		97
	Invalid orientation	96	96		99

Table 6.1. Mean percentage of correct responses across all experiments in Chapter 6.

Figure 6.2 indicates systematic variations between RTs and displays depending on the type of cue. Contrasts across display type (Small, Equal and Large cue conditions) were therefore calculated for each type of cueing. The benefit from valid colour cueing increased as the size of group cued increased (linear component of main effect of group size for valid colour cues; $F(1,17)=4.3$, $p=0.055$, partial $\eta^2=0.2$) as did the cost from invalid colour cues (linear component of main effect of group size for invalid colour cues; $F(1,17)=16.6$, $p=0.001$, partial $\eta^2=0.495$). In contrast, the effect of valid orientation cues decreased with the increasing number of stimuli matching the cue (linear component of main effect of group size for valid orientation cues; $F(1,17)=3.8$, $p=0.067$, partial $\eta^2=0.184$) as did the effect following invalid orientation cues (linear component of main effect of group size for invalid orientation cues; $F(1,17)=4.6$, $p=0.047$, partial $\eta^2=0.212$).

Accuracy. There was no speed-accuracy trade-off. The mean accuracy data are shown in Table 6.1.

Eye movements. For each trial eye movements were recorded as previously and the data of the first two fixations cleaned and the nearest item to the fixation-location calculated[11].

Frequency of target-fixations (first two fixations). As a measure of search guidance, the mean frequency of the first and second fixation being directed to the target was computed (cf. Findlay, 1997). The data from the uncued, neutral condition (see Experiment 5.1 for details) were used as the baseline and only the effects of cueing on the frequency of target-fixations were analysed. The data were divided according to fixation number, display type, cue dimension and cue validity. The data were controlled for chance to scale the data to match the baseline (see Experiment 5.1 for details). Figure 6.3 shows mean frequencies of the first and second fixations being directed to the target in the cue conditions minus the neutral condition.

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[11] Fixation-item distances here and throughout Chapter 6 mirrored those outlined in Experiment 5.1. For arguments about the suitability of this assignation see 5.1.3.

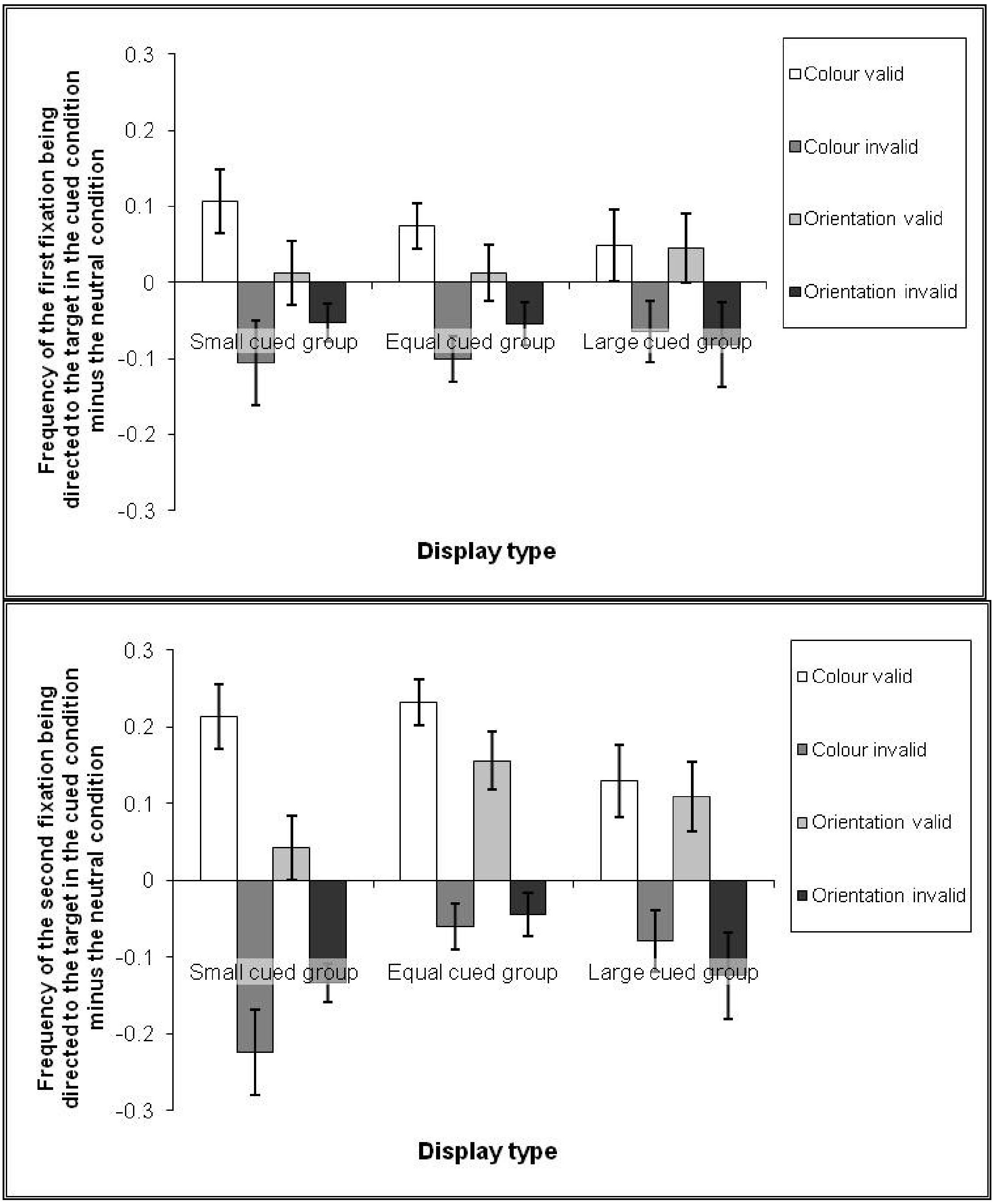

Figure 6.3. Means (+/- one standard error) of the mean frequency of the first and second fixations being directed to a search target in the cue condition minus the neutral condition in Experiment 6.1. There data were adjusted for chance and separated by display type (see Figure 6.1), cue dimension and cue validity.

For clarity, data from first and second fixations were analysed separately. Analysing cueing effects on first fixation, a three-factor ANOVA (display type, cue dimension, cue validity) showed a significant main effect of cue validity (F(1,16)=12.3, p=0.003, partial η^2=0.435) with valid cues biasing search towards the target (a positive effect of 0.05) while invalid cues directed search away from the target (a negative effect of -0.077), relative to baseline. No other main effects or interactions reached significance (all ps>0.1).

Analysis of the second fixation data indicated larger cueing effects, compared with the data for first fixations (see Figure 6.3). There were main effects of cue validity (F(1,16)=18.3, p=0.001, partial η^2=0.534) and display type (F(2,32)=3.6, p=0.043, partial η^2=0.179). As with the initial fixation, valid cues directed fixations towards the target (a positive effect of 0.147) while an opposite effect was evident following invalid cues (a negative effect of -0.111). The main effect of display type reflected differences in the overall effect of cueing (valid-invalid effects) as the size of the cued group varied. The effect of cues were negative when the smaller group was cued (a combined cueing effect of -0.026), indicating a stronger effect of invalid cues compared to the effects of valid cues, and the net effect of cues reducing target-fixations relative to the neutral uncued condition. In contrast, when the distractor ratio was balanced there was an overall benefit from cues (a net effect of 0.071) reflecting an advantage for valid cueing effects in increasing target-fixations. Cueing effects were matched when cues matched the larger group of distractors (a net effect of 0.009). There was also a borderline significant cue dimension x cue validity interaction (F(1,16)=3.4, p=0.084, partial η^2=0.175). The bias towards fixating the target was greater following valid colour cues compared to valid orientation cues (an effect of 0.089, p=0.004) while no such difference was evident between the effects of invalid cueing (an effect of 0.02, p=0.663).

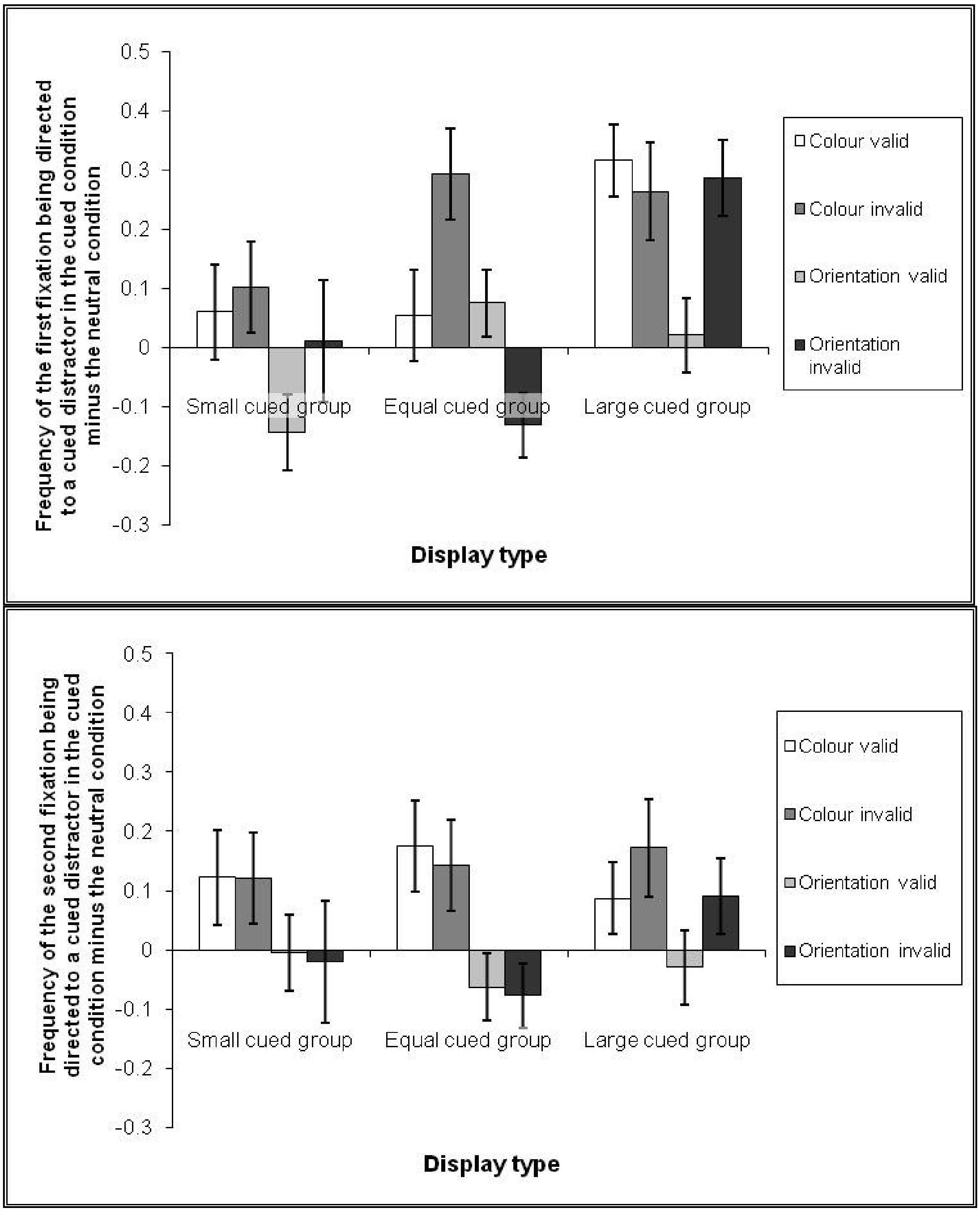

Figure 6.4. Means (+/- one standard error) of the mean frequency of the first and second fixation being directed towards a distractor with the cued feature in the cue condition minus the neutral condition in Experiment 6.1. Data were adjusted for chance and separated by display type (see Figure 6.1), cue dimension and cue validity.

Frequency of fixating a cued distractor (first two fixations). To further investigate the guidance from cues, I looked at their effect on the frequency of a fixation to a distractor with the same feature as the cue. To avoid biases from fixations directed to the target stimulus itself (cf. Shen et al., 2000), trials where the target was fixated either on the first or second fixation were removed. The results were again controlled for chance (see Experiment 5.1 for details) and then compared to the corresponding data from a neutral cue condition. See Figure 6.4.

As previously, the data from each fixation were analysed separately. A three-factor ANOVA (display type, cue dimension, cue validity) analysing first fixation data found main effects of cue dimension (F(1,16)=19.7, $p<0.001$, partial $\eta^2=0.552$), display type (F(1.561,16.855)=5.8, p=0.026, partial $\eta^2=0.267$), and cue validity (F(1,16)=5.2, p=0.036, partial $\eta^2=0.246$). Relative to baseline, there was a stronger increase in the frequency of fixations to a cued distractor following colour cues compared to orientation cues (increases of 0.182 vs. 0.02). The effects of cueing increased with the size of group matching the target, with the largest effect when the large group was cued (Large group vs. Equal group cued, a difference of 0.149, p=0.012; Large group vs. Small group cued, a difference of 0.215, p=0.089). There was no difference between the effect when the Small vs. Equal group was cued (a difference of 0.066, p=0.595). Cueing effects were larger on invalid trials, with invalid cues increasing fixations to cued distractors to a greater extent than valid cues (increases of 0.138 vs. 0.064 respectively).

There was also a three-way interaction (F(1.272,20.356)=4.8, p=0.032, partial $\eta^2=0.231$), which arose due to a larger increase in fixations being directed to cued distractors following valid colour cues compared to valid orientation cues when cues matched either the small or large subset of distractors (differences between valid colour and orientation effects of 0.203, p=0.04, and 0.297, p=0.001). In contrast, when the ratio was balanced there was a larger increase in cued distractor-fixations following *invalid* colour cues compared to *invalid* orientation cueing (Equal cued group, difference of 0.425, p=0.001). It should be noted that valid cues that matched the orientation of the smaller subset of distractors and invalid orientation cueing when the distractor ratio was balanced decreased the fixations being directed to cued distractors, relative to baseline (t(16)=2.234, p=0.04 and t(16)=2.435, p=0.027, respectively).

Analysis of cueing effects on second fixations indicated a main effect of cue dimension (F(1,16)=18.4, p=0.001, partial η^2=0.535). There was a larger increase in the likelihood of fixating distractors matching the feature of the cue when this value was colour rather than orientation (0.137 vs. -0.017, respectively), while no other main effects or interactions reached significance (all ps>0.1).

6.1.4: Discussion

The RT data indicated that valid cues facilitated search while RTs were longer following invalid cues, and this effect of validity was larger following a colour than an orientation cue when there were equal groups of distractors or when participants were cued to the larger group. These results replicate those of Anderson et al. (2010). In contrast, when participants were cued to the small group of distractors the effects of validity were greater after an orientation cue. The pattern of effects, moreover, indicated that the influence of colour cues increased with the number of stimuli cued, while the opposite correlation was evident for orientation cues. This was reflected by the lack of a difference between colour and orientation cueing when the small group was cued (the effects of colour were at a minimum while those following orientation were at a maximum) and the largest difference being when the large group was cued (colour cueing effects were at a maximum, orientation cueing at a minimum).

The eye movement data presented a complementary pattern of results. In terms of fixations to targets, there were relatively small effects of cueing at first fixation. The main results being a ‘validity effect’: valid cues increased the likelihood of a target-fixation, invalid cues decreased this frequency. Clearer validity effects emerged at second fixations with the overall effect from cueing (e.g., valid-invalid cues) varying across display type. When the cue was to the small group (see Figure 6.1a), there was a negative effect on fixations, reflecting a stronger effect from invalid cues directing fixations away from the target and towards distractors compared to baseline. It should be noted that target-fixations were increased on the corresponding displays on neutral baseline trials compared with when distractor ratios were balanced. The stronger effect of invalid cueing may, therefore, be due to reduced effects from valid cues on target-fixations reaching ceiling following an existing bias in the baseline data. In contrast, when the distractor ratio was balanced (see Figure 6.1b) there was an overall benefit from cues – a positive effect – indicating stronger effects from valid cueing. As no guidance was available from distractors on displays with even distractor subsets, the target would have had more influence on search (see Chapter 5). Therefore, effects of information matching the target may be more robust that effects of invalid cues. Effects of valid and invalid cues were more balanced when the cue feature matched that of the Larger group (Figure 6.1c). This suggests that valid and invalid cues were equally successfully in counteracting the opposing bias in the baseline trials towards fixating the smaller subset of stimuli (see Experiment 5.1).

There was also a trend across display types towards strong guidance towards the target from valid colour compared to valid orientation cues, however this did not vary with display type. This suggests the differences in RTs were not due to differences in the ability of the cue to aid segmentation of the target.

The pattern of the cueing effects on distractor-fixations may be more pertinent to the pattern of effects on RTs. Across display types, cues directed initial fixations towards distractors with the same feature value to a greater extent when the cued subset was in the majority (see Figure 6.1c), compared to the other two conditions (see Figures 6.1a and 6.1b). Again, this suggests that cueing effects were reduced when the smaller group was cued perhaps due to the existing bias in the neutral condition (smaller-subset search, Sobel & Cave, 2002). However, this bias varied depending on the type of cue. When the cue matched either the minority of majority subset of distractors, colour cues increased fixations to these stimuli to a greater extent than orientation cues. Indeed, when cueing the small group (Figure 6.1a) of items, colour cues increased fixations to this group compared to the neutral baseline (see experiment 5.1), however orientation cues decreased eye movements to the cued stimuli. When the large group was cued (Figure 6.1c), orientation cueing effects were negligible relative to strong effects of colour cues.

A different pattern was evident when distractor ratios were balanced (Figure 6.1b). Following invalid colour cues, there was an increase in fixating distractors with the designated colour. A similar yet opposite effect was event on invalid orientation trials, with cues decreasing fixations to distractors with the cued orientation relative to the neutral baseline. Effects on distractor-fixations were reduced at second fixations and did not vary with display type. However, colour cues directed eye movements towards distractors with the cued colour more effectively than orientation cues.

How can these data be explained? To account for the results we can think of search as being affected by both bottom-up and top-down factors. First there are bottom-up factors that may parse elements into sub-groups and draw attention to the smaller sub-group of distractors (e.g., Sobel & Cave, 2002). Second, there may be top-down factors that influence the initial parsing and attentional guidance to the sub-groups (e.g., favouring the selection of the cued group). Third, bottom-up and top-down factors may combine to influence the selection of the target from within a particular group of distractors. Each of these processes may be differentially efficient for the dimensions of colour and orientation. For example, either or both bottom-up or top-down grouping and guidance of search to a small group may occur faster if elements group by colour compared with when they group by orientation. Similarly, within a selected group, segmentation of the target from the distractors may be faster along the colour dimension compared with the orientation dimension. Given that there were reliable effects of which dimension was cued, there is evidence for top-down influences on selection.

The correlation between the effects of colour and orientation cueing on search RTs and the size of the cued group indicate differential relationships between the two dimensions and the number of stimuli matching the cue feature. On RTs colour cueing effects increased with group size, while orientation cueing decreased. One proposal explaining this pattern is that the stimuli are rapidly grouped into colour-defined subsets, and this would occur in the neutral condition (where search would be biased towards stimuli in smaller colour groups, see Chapter 5) as well as the cued conditions (here). The effect of colour cueing on RTs would be small when the smaller group of stimuli is cued, because there is already a bottom-up bias towards fixating the minority colour group (cf. Sobel & Cave, 2002). In essence, search behaviour may have reached ceiling. However, a cue to a large colour group may be effective because it then counteracts the bottom-up bias to the small colour group (which would be made up of distractors in this case). This situation will reverse for orientation cues. Irrespective of the orientation cue, the stimuli may already be parsed into small and large colour groups. An orientation cue to a large orientation group may have relatively little effect because the target will already be segmented into the minority colour group. An orientation cue to a small orientation group may be effective however, because in this condition the target will be assigned by bottom-up processes into the larger colour group; by working against this assignment into the majority group, the orientation cue may benefit performance. For example, on a trial with a valid horizontal cue matching the small subset of distractors (see Fig. 6.1a), the target would be grouped with the larger blue group of distractors. The horizontal cue may counter this grouping, by enhancing the local orientation disparity of the target within the blue subset.

The eye movement data on displays with uneven ratios were largely consistent with this proposal. However, a somewhat different pattern was evident when the distractor ratio was balanced. Invalid colour cues increased fixations to cued distractors while invalid orientation cues decreased this frequency. It may be that little guidance was available from the even-numbered subsets of distractors (Duncan & Humprheys, 1989), and if prior information about target-orientation was incorrect, salience effects from local differences within that dimension may also be diminished. Therefore, search may be primarily be directed by target-colour, rather than the orientation of the cue, within a search array grouped by colour. The target would therefore be a colour singleton within one of colour-defined subsets (see Fig. 6.1b). This local colour disparity may guide eye movements so fixations not to the target were directed towards the subsets whose colour opposes that of the target and did not match the cue in orientation. On an invalid trial with a vertical cue and a balanced ratio display, for example (see Fig. 6.1b), the target would be a blue horizontal singleton within the green horizontal group. Search may be initially directed towards colour-group which the target differs in colour (e.g., the green colour group). The colour of this group may then be used to guide search. Invalid colour cues, in contrast, would direct attention directly towards the group with the pop-out target. These stimuli match the cue in colour.

As mentioned above, the top-down information from the cue may multiply any bottom-up signals based on differential grouping and segmentation of small and larger groups. This multiplicative effect may be most effective from a visual top-down cue. Experiment 6.2 set out to test whether these top-down effects would also emerge with verbal cues, comparing the two types of cue in a within-participant design. I also lengthened the duration of the cue prior to the search display. In Experiment 6.1, I found evidence of a bias towards non-cued distractors (sharing the colour linked to the cue feature via the target) following orientation cues. This pattern of guidance from orientation cues may emerge over time. In Experiment 6.2, when the cue is presented for longer cueing of attention towards stimuli differing to the cue's orientation could be more robust.

Experiment 6.2: Visual vs. Verbal Cues

6.2.1: Introduction

Wolfe et al. (2004) found that verbal inter-trial cues required longer stimulus onset asynchronies to generate equivalent cueing effects to visual cues. Anderson et al. (2010) too found comparable effects on search speed from both orientation cues and colour cues when the cues were presented for longer durations (e.g., 1200ms, see Chapter 3). Experiment 6.2 used this longer duration for both visual and verbal cues.

With cue durations of 1200ms there should be time to decode the cue information and orient to appropriate target information.

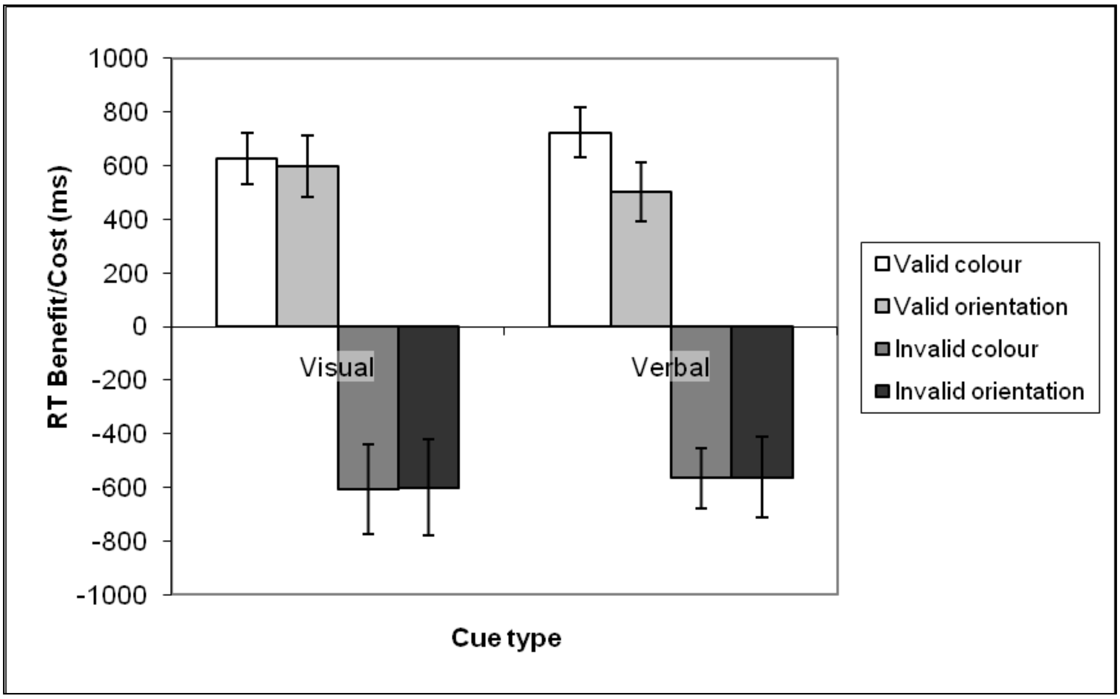

Figure 6.5. Means (+/- one standard error) of RT Benefits/Costs from Experiment 6.2, separated by cue type, cue validity and cue dimension.

6.2.2: Method

The method was largely the same as in Experiment 6.2, except where mentioned below. The search displays always used equal numbers of distractors.

Participants. Eighteen University of Birmingham students, three male, 15 female, aged 18-28 (average 20.94) took part.

Design. There were four main independent variables: cue type (visual or verbal), cue validity (valid, neutral, invalid), cue dimension (colour, orientation), and target type (blue horizontal, green vertical).

Stimuli. Neutral trials matched the balanced ratio condition in Experiment 5.1. On cued trials two types of predictive stimuli were used. In the visual cue condition, the cues matched those in Experiment 6.1. For the verbal cue condition, complete words were used to cue the colour or orientation, with the words *GREEN*, *BLUE*, *VERTICAL* and *HORIZONTAL* presented in black capitals using an Arial font. The length of word varied from 3.2cm (3.1°) to 7.8cm (7.4°), with all words 0.8cm tall (visual angel of 0.8°) with a thickness of 0.2cm (0.2°).

Procedure. Participants took part in two blocks of trials, with the nature of the cue consistent for each block. Verbal cue trials matched the trials in Experiment 6.1, except the visual cues were replaced by words (see Stimuli section) which were presented for 1200ms. Visual cued trials followed those in Experiment 6.1, except cues were presented for 1200ms. For each cue type, there were 120 trials with the number of practice trials varying from 30 to 40. The distractor ratio was balanced on all trials (see Equal group cued, Figure 6.1). Block order was counterbalanced.

6.2.3: Results

RTs. Data were cleaned as in Experiment 6.1. Data were averaged across target type and for parsimony only the effects of cueing were analysed.

RT Cost-Benefits. For each participant, median RTs from cued conditions were subtracted from the corresponding data on neutral trials[12]. See Figure 6.5 for mean values across participants.

A three-factor ANOVA (cue type, cue dimension, cue validity) showed no effects of cue type (whether the cue was visual or verbal; $F<1$). There was a main effect of validity ($F(1,17)=170.8$, $p<0.001$, $\mu^2=0.909$), with a benefit from valid cues

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[12] The neutral data were used as baseline. Details are not outlined here but are available on request.

(612ms) and a cost from invalid cues (-583ms) but the dimension x validity interaction failed to reach significance (F(1,17)=1.9, p=0.184, μ^2=0.102). No other main effects or interactions reached significance.

Accuracy. There was no speed-accuracy trade-off (see Table 6.1).

Eye movements. The eye movement data were treated previously, and the nearest item to each of the first two fixations on each trial was assessed. See Experiment 5.1.

Frequency of fixating the target (first two fixations). The effect of cueing on the mean frequency of the target-fixations was calculated as previously Data were adjusted for chance and the mean differences relative to the neutral condition are shown in Figure 6.6.

As previously, the data from the first and second fixations were analysed separately. At Fixation 1, a three-factor ANOVA (cue type, cue dimension, cue validity) found a main effect of cue validity (F(1,17)=35.9, p<0.001, partial η^2=0.689). Compared to the neutral baseline, valid cues directed fixations towards the target to a greater extent than invalid cues (adjusted probabilities of 0.119 and -0.015, respectively). No other main effects of interactions reached significance (all ps>0.1). At Fixation 2, there was a main effect of validity (F(1,17)=82, p<0.001, partial η^2=0.828), with valid cues increasing fixations towards the target (a positive effect of 0.215) while invalid cues decreasing this measure (a negative effect of -0.148). There was also a cue dimension x cue validity interaction (F(1,17)=22.8, p<0.001, partial η^2=0.573) indicating stronger effect of colour cueing (a validity effect of 0.477, p<0.001) compared to when the orientation of the target was cued (a validity effect of 0.247, p<0.001). There was a three-way interaction (F(1,17)=4.6, p=0.047, partial

η^2=0.213), suggesting that the colour advantage varied across cue type (verbal or visual).

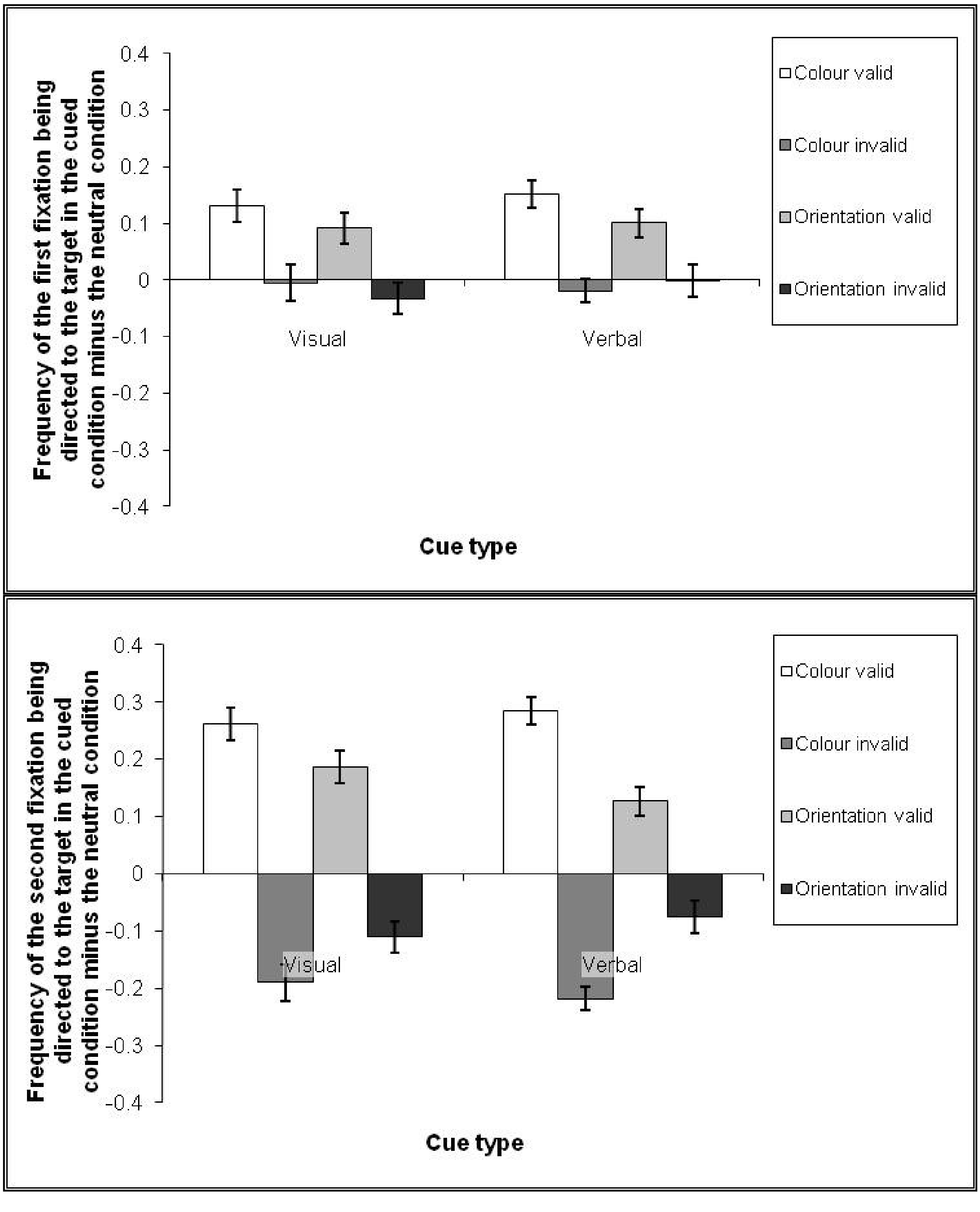

Figure 6.6. Means (+/- one standard error) of the mean frequency of first and second being directed to the target in the cued condition minus the corresponding data in the neutral condition, in Experiment 6.2. The data were adjusted for chance and separated by cue type, cue validity and cue dimension.

Frequency of fixating a cued distractor (first two fixations). The effect of cueing on the frequency of fixation a cued distractor was calculated as previously. Figure 6.7 shows the frequency of the first and second fixation directed to a cued distractor minus the corresponding data in the neutral condition. Data from first and second fixations were analysed separately.

For the first fixation data, a three-factor ANOVA (cue type, cue dimension, cue validity) found a reliable main effect of dimension ($F(1,17)=78.5$, $p<0.001$, partial $\eta^2=0.822$). Colour cues increased the likelihood of a fixation being directed to a cued distractor while orientation cues decreased this frequency (effects of 0.231 vs. -0.079). Both effects significantly differed from the neutral condition (colour, $t(17)=10.882$, $p<0.001$; orientation, $t(17)=-2.772$, $p=0.013$, both one-tailed). No other effects or interactions were reliable (all $ps>0.15$).

Analysis of the second fixation data reinforced the pattern from the first fixation data. There were reliable main effects of cue dimension ($F(1,17)=41.5$, $p<0.001$, partial $\eta^2=0.709$) and cue validity ($F(1,17)=10.5$, $p=0.005$, partial $\eta^2=0.382$). Colour cues led to an increase in fixations directed to cued distractors (a positive effect of 0.238), while orientation cues decreased this likelihood (a negative effect of -074). Again, these effects differed from the neutral condition (colour, $t(17)=7.238$, $p<0.001$; orientation, $t(17)=-2.864$, $p<0.001$, both one-tailed). There was also a cue dimension x cue validity interaction ($F(1,17)=7.816$, $p=0.012$, partial $\eta^2=0.315$). There were larger increases in fixations to a cued distractor from valid colour cues compared increases following invalid colour cues (a difference of 0.195, $p=0.002$). The difference between the effects of valid and invalid orientation cues did not reached significance ($p>0.133$).

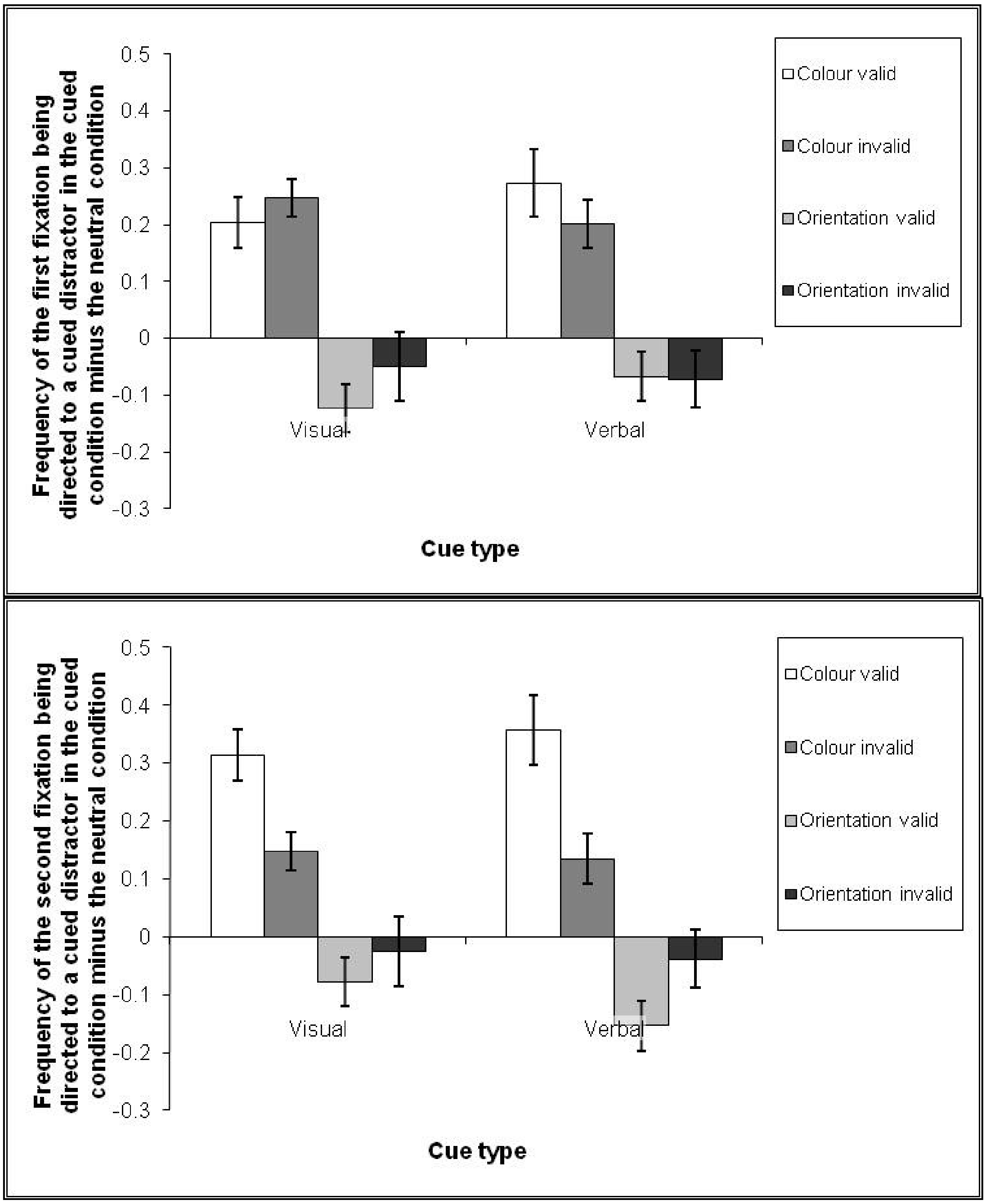

Figure 6.7. Means (+/- one standard error) of the mean frequency of first and second fixations being directed to a cued distractor in the cued condition minus the corresponding data in the neutral condition, in Experiment 6.2. The data were adjusted for chance and were separated by cue type, cue validity and cue dimension.

Comparisons across experiments. To examine how varying the cue duration altered the guidance available from visual cues, comparisons of cueing effects were undertaken across Experiments 6.1 and 6.2. Only trials with equal numbers of distractors were included. For parsimony, only main effects of, and interactions with, experiment number are reported.

Exp. 6.1 vs. 6.2: RT Cost-Benefits. The effects of visual cueing at short durations (200ms, Experiment 6.1) were compared with those from longer cues (1200ms, Experiment 6.2), using a three-factor, mixed design ANOVA (experiment number, cue dimension, cue validity). There was an interaction between cue dimension and experiment ($F(1,34)=8.5$, $p=0.006$, $\mu^2=0.2$), with a larger benefit relative to the neutral baseline following colour cues compared with orientation cues for Experiment 6.1 (short duration; a difference 210ms, $p<0.001$) compared with Experiment 6.2 (long duration; a difference of 11ms, $p=0.825$). There was also a cue validity x experiment interaction ($F(1,34)=7.3$, $p=0.01$, $\mu^2=0.178$), with a larger cueing effect following the long relative to short duration cues (1215ms vs. 814ms, respectively, both $ps<0.001$). Neither the main effect of experiment number nor three-way interaction reached significance ($Fs<1$).

Exp. 6.1 vs. 6.2: Frequency of target-fixations (first two fixations). The effects of short duration (Experiment 6.1) and long duration (Experiment 6.2) cues on the frequency of target-fixations were analysed separately for first and second fixations. At fixation 1, there was only a main effect of experiment ($F(1,33)=4.5$, $p=0.04$, $\mu^2=0.122$). This showed that, on balance, longer cues increased target-fixations compared to shorter cues (Experiment 6.2 vs. Experiment 6.1; effects of 0.046 vs. -0.017, respectively). Analysis of the second fixation data showed a borderline cue validity x experiment interaction ($F(1,33)=3.3$, $p=0.08$, partial $\eta^2=0.09$) reflecting a trend towards a larger validity effect following longer cues (Experiment 6.2; a difference of 0.374, $p<0.001$) relative to shorter cues (Experiment 6.1; a difference of 0.246, $p<0.001$).

Exp. 6.1 vs. 6.2: Frequency of fixating a cued distractor (first two fixations). How the variation in the cue duration across Experiments 6.1-6.2 affected whether the first fixation was directed towards a cued distractor was also assessed. There was a three-way interaction ($F(1,33)=4.5$, $p=0.041$, partial $\eta^2=0.12$). Compared to the neutral condition, there was a greater decrease in fixations to distractors matching the orientation of a cue (e.g., directing fixations towards distractors not sharing the cue orientation) following cues presented for 1200ms compared to 200ms (Experiment 6.2 vs. Experiment 6.1, a difference between effects of valid orientation cues of 0.199, $p=0.007$). No other main effects or interactions with experiment reached significance. Similar analysis of the second fixation data showed no significant main effects or interactions (all $ps>0.1$).

6.2.4: Discussion

Under the conditions examined in Experiment 6.2, there were equally strong cueing effects from visual and verbal cues. This suggests that cue information may be held in a relatively abstract manner in working memory and feedbacks to influence visual representations of the stimuli in search (cf. Soto & Humphreys, 2007). Alternatively, the cue durations may have been sufficiently long to enable participants to form images of the targets and the visual representations of the stimuli affected search (e.g., Huettig & Altmann, 2005; Moores, Laiti, & Chelazzi, 2003). Irrespective of exactly how the verbal cue influenced target selection, the present data emphasise that the cueing effects here could not have been due to perceptual priming from the cue. There can be genuinely top-down effects and these top-down effects are stronger from colour than from orientation cues.

As well as examining modality effects in cueing, this experiment evaluated the effects of cue duration on visual cues. Overall, the effects of cue validity increased at longer cue durations. On RTs the greater validity effect was most evident in terms of the greater cost on invalid trials (compare Fig. 6.2 and Fig. 6.5). This suggests that following long colour cues it became more difficult to disengage attention from incorrectly cued distractors. On top of this, the effect of the colour cue was relatively stronger than the effect of the orientation cue in Experiment 6.1 compared with Experiment 6.2. There may be some bottom-up priming of colour that guides attention more than the bottom-up priming of orientation (at short cue-search display intervals, see Chapter 4), or it might be that colour-templates are more rapidly implemented to guide search in a top-down manner.

The eye movement evidence indicated that, as the cue duration increased, two effects were evident. One is that there was greater guidance of attention to the target rather than distractors following a colour cue. The second is that there was a stronger bias against fixations being made to the cued orientation. Note that no bias towards fixating a particular distractor type was evident in the baseline, neutral condition (see Experiment 5.1). As was proposed previously, this may be due to participants re-orienting attention based on colour-grouping between the items. If, on failing to select the target, attention is directed to the ‘other’ group of distractors (defined by their colour), then the probability of fixating a distractor with the cued orientation would decrease. This misdirection may be due to the target acting as a colour singleton within the group (on invalid trials). On valid trials the orientation of the cue and target match. The misdirection on these trials may therefore this may be a consequence of participants coding the colour of the target, with this feature then guiding search. Alternatively, it may be that with the longer cue duration, participants have enough time to translate the orientation information into the associated colour. For example, a vertical cue would be linked to searching green search items via the identity of the target – a green vertical bar. Previous studies have shown eye movements are directed to objects associated with information presented prior to a trial (Moores, Laiti, & Chelazzi, 2003). See 1.5.4.5 for details. Search would therefore be determined by the colour associated with the cue rather than the orientation.

Experiment 6.3: Varying the Spatial Layout of Distractors

6.3.1: Introduction

Experiment 6.1 demonstrated opposite effects of group size on the effects of colour and orientation cues. Colour cues to a large group generated stronger benefits and costs on RTs, while cueing orientation to the small group generated a larger effect than cueing attention to the large group. I suggest that effects on eye movements complement this. In the former case, following colour cueing, search may be directed to a large colour group. Search would then be guided towards the target via a local orientation disparity (valid cueing; Friedman-Hill & Wolf, 1995) or would suffer a disengagement cost if the target was not within this subset (invalid cueing; Anderson et al., 2010). Effects of orientation cues, however, were lessened as the smaller colour group could be used to guide search. If the smaller distractor subset matched the cue there would be less of an effect of cueing due to the existing bias in the neutral condition. Colour cues would again direct attention more efficiently, moreover, operating in parallel with the bias towards searching the colour subset reflected in the absence of cueing (see Experiment 5.1).

Experiment 6.3 was designed to test the sensitivity of the apparent grouping and top-down cueing effects to the local spatial relations between the stimuli. There were three conditions where the spatial relationship between distractor types was manipulated. Search arrays in Colour segmented and Orientation segmented conditions were designed to facilitate local grouping within the respective dimensions, with adjacent distractors sharing either their colour or their orientation. In the Mixed condition, adjacent stimuli varied in colour and orientation. If there are effects of distractor grouping on target detection, then performance should be modulated by whether the distractor elements are locally grouped or not. In addition, it is possible that local disparities between the target and distractor could help direct attention to the target – for example, a local orientation disparity cue could signal an orientation-defined target within a colour group. There may then be few differences between colour and orientation cues. In contrast, with elements in random locations colour cueing may be more effective (Experiments 6.1-6.2 here). This would suggest that colour cueing facilitated global grouping effects, which would tend to be weak with Mixed (e.g., heterogeneous) rather than spatially grouped displays.

6.3.2: Method

The methodology was the same as Experiment 6.2, with the differences outlined below.

Participants. Twenty students from the University of Birmingham took part, aged 18-30 (average 22.05), with 13 females, seven males.

Design. There were four main independent variables: display type (Mixed, Colour segmented, Orientation segmented, see Figure 5.9, cue dimension (colour, orientation) and cue validity (valid, neutral, invalid).

Procedure. Cued trials matched that of Experiment 6.2, except only verbal cues were presented prior to each display during both blocks of 120 trials. Neutral trials are outlined in Experiment 5.2.

6.3.3: Results

RTs. Data were cleaned as previously. Data were averaged across target type and for parsimony only the effects of cueing were analysed[13]. For clarity, analysis of data from the Mixed condition was undertaken separately to the data from the Colour and Orientation segmentation conditions.

RT Cost-Benefits. As previously, the effect of cueing on search speed was calculated by subtracting median RTs from cued conditions the corresponding data from neutral trials. Mean values are shown in Figure 6.8.

Analysis of the data from the Mixed condition was conducted using a two-factor ANOVA (cue dimension, cue validity). There was a main effect of cue validity ($F(1,19)=291.4$, $p<0.001$, partial $\eta^2=0.939$) and a significant interaction ($F(1,19)=6.2$, $p=0.022$, partial $\eta^2=0.245$). There was larger modulation following colour cues (a difference of 1326ms, $p<0.001$) compared to orientation cues (a difference of 1096ms, $p<0.001$).

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[13] The neutral condition was used as a baseline measure and is outlined in Experiment 5.2.

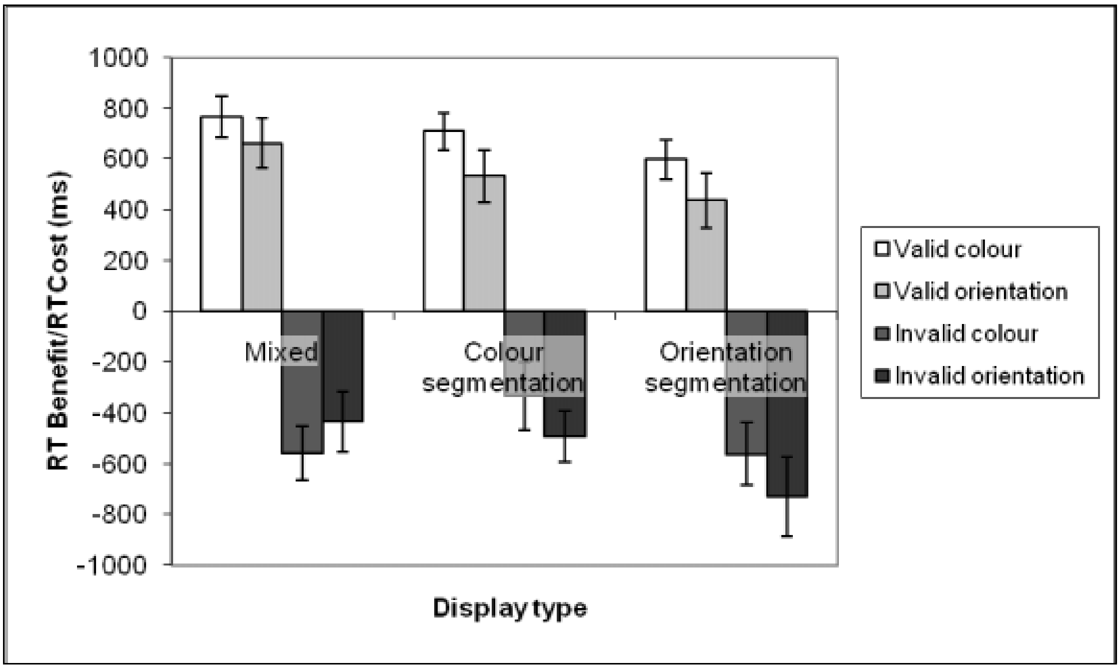

Figure 6.8. Means (+/- one standard error) of RT Benefits/Costs, separated by cue validity, cue dimension and display type (see Figure 5.0) from Experiment 6.3.

The data from the Colour and Orientation segmentation conditions were analysed together in a three-factor ANOVA (display type, cue dimension, cue validity). There were main effects of cue validity (F(1,19)=181.2, $p<0.001$, partial $\eta^2=0.905$) and cue dimension (F(1,19)=17.9, $p<0.001$, partial $\eta^2=0.485$), as well as a borderline significant effect of display type (F(1,19)=3.4, $p=0.08$, partial $\eta^2=0.153$). Valid cues facilitated search while invalid cues led to longer RTs (effects of 568ms and -530ms, respectively), relative to the neutral baseline. There was also a greater facilitation effect on trials when the cue predicted the colour of the target relative to when the target-orientation was cued (effects of 102ms and -64ms, respectively). In the Colour segmentation condition, valid cueing was stronger than invalid cueing (an overall effect of 103ms) while in the Orientation segmentation condition the effects of valid and invalid cueing were more balanced (an effect of -63ms).

Accuracy. There was no speed-accuracy trade-off (see Table 6.1).

Eye movements. The eye movement data were treated as before, with the frequency of the first and second fixation being directed to a particular array stimulus calculated for each participant in each condition. Due to errors in the calibration procedure, the data from one participant were discarded.

Frequency of fixating the target (first two fixations). As in Experiments 6.1-6.2, the effect of cueing on the frequency of either the first or second fixation being directed to the target was calculated by subtracting the frequency in the neutral baseline condition, where no cue was present, from the data in the corresponding cued condition. Data had been previously been controlled for chance (see Experiment 5.1 for details). Group means are shown in Figure 6.9. Data from the first and second fixations were analysed separately.

A two-factor ANOVA (cue dimension, cue validity) was used to analyse the effect of cueing on initial fixations on Mixed trials. No main effects or interactions reached significance (all ps>0.1). The first fixation data from the Colour and Orientation segmentation displays were then analysed using a three-factor ANOVA (cue dimension, cue validity, display type). There was a display type x cue validity interaction (F(1,18)=6.4, p=0.021, partial η^2=0.263). In the Orientation segmentation condition, valid cues increased the fixations directed to the target relative to invalid cues (an effect of 0.088, p-0.004), while no similar effect was evident on Colour segmentation displays (an effect of 0.032, p=0.553).

Analysis of the second fixation data from the Mixed condition found a main effect of cue validity (F(1,18)=49, p<0.001, partial η^2=0.731). Valid cues increased the fixations directed to the target (an effect of 0.105) and invalid cues decreased this frequency (an effect of -0.07). There was also an interaction (F(1,18)=49, p<0.001, partial η^2=0.731), indicating that this validity effect was larger following colour cues (an effect of 0.222, p<0.001) compared to orientation cues (an effect of 0.128, p=0.001).

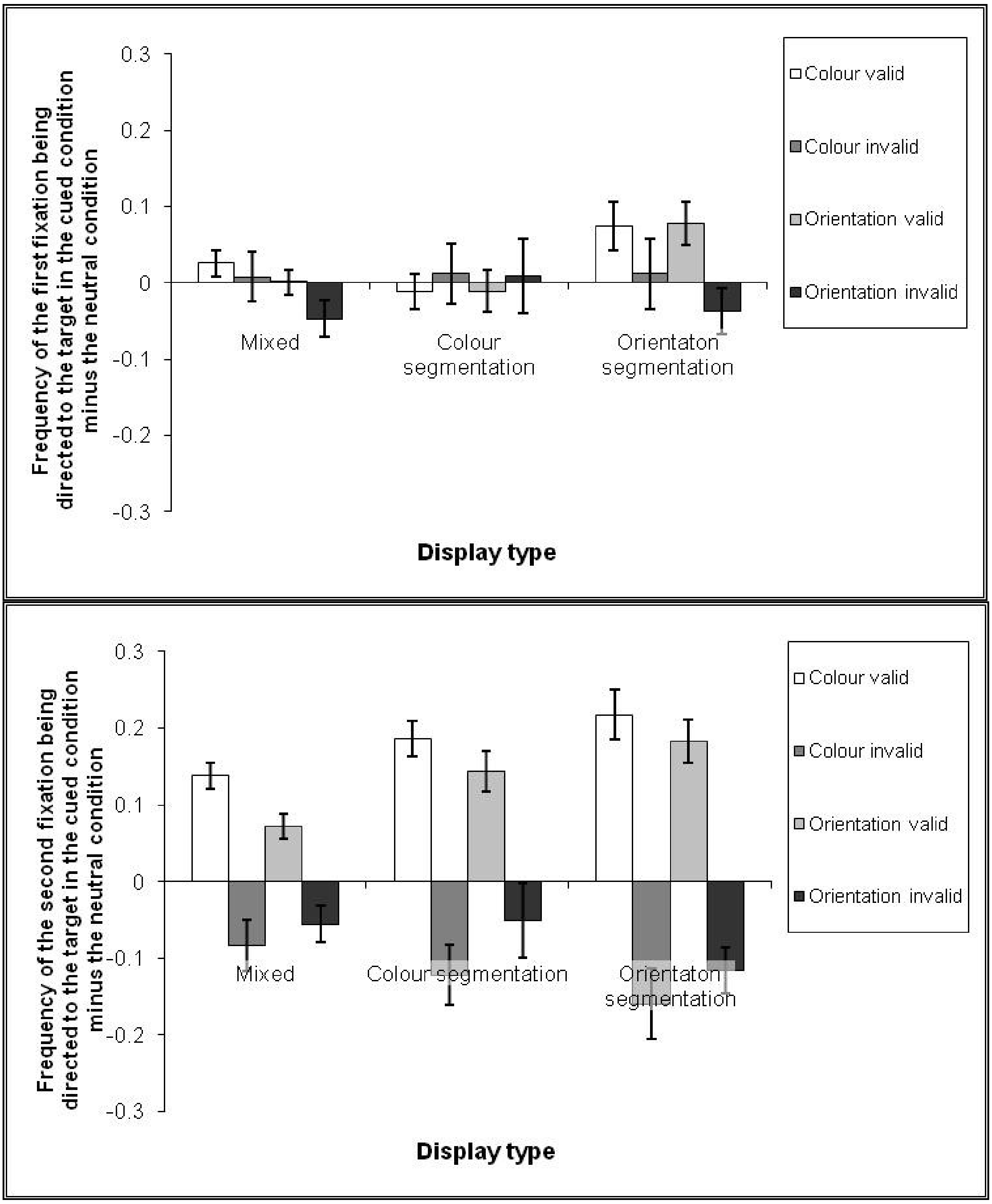

Figure 6.9. Means (+/- one standard error) of the mean frequency of first and second fixations being directed to a the target in the cued condition minus the corresponding data in the neutral condition, in Experiment 6.3. The data were adjusted for chance and were separated by cue type (see Figure 5.9), cue validity and cue dimension.

Analysis of second fixation data from Colour and Orientation segmentation displays revealed a main effect of validity (F(1,18)=103.2, $p<0.001$, partial $\eta^2=0.851$). Valid cues increased target-fixations (an effect of 0.183) while invalid cues decrease this frequency (an effect of -0.112). There were also two interactions: display type x cue validity (F(1,18)=5.7, p=0.028, partial $\eta^2=0.24$) and cue dimension x cue validity (F(1,18)=6, p=0.024, partial $\eta^2=0.251$). Cueing effects were larger when the target differed to local items in orientation compared to when the target differed in colour (validity effect in the Orientation Segmented condition of 0.338, $p<0.001$; validity effect in the Colour Segmented condition of 0.252, $p<0.001$). There were stronger validity effects from colour cues compared with orientation cues (colour validity effect of 0.343, $p<0.001$; orientation validity effect of 0.247, $p<0.001$), but this bias did not differ across display type (three-way interaction: $F<1$).

Frequency of fixating a cued distractor (first two fixations). The cueing effect on the frequency of a fixation being directed to a cued distractor was calculated as previously. Means across participants are shown in Figure 6.10. As previously, data from the first and second fixations were analysed separately.

Analysis of the cueing effect on the first fixations to cued distractors in the Mixed condition was conducted using a two-factor ANOVA (cue dimension, cue validity). There was no main effects or interactions (all ps>0.1).

Analysis of first fixation data from the Colour and Orientation segmentation conditions showed a main effect of cue dimension (F(1,18)=39.8, $p<0.001$, partial $\eta^2=0.689$), with a strong increase in the likelihood of a fixation being directed to a cued distractor following colour cues (a positive effect of 0.7) relative to the effects following orientation cues (-0.024). No other main effects or interactions reached significance (all ps>0.18).

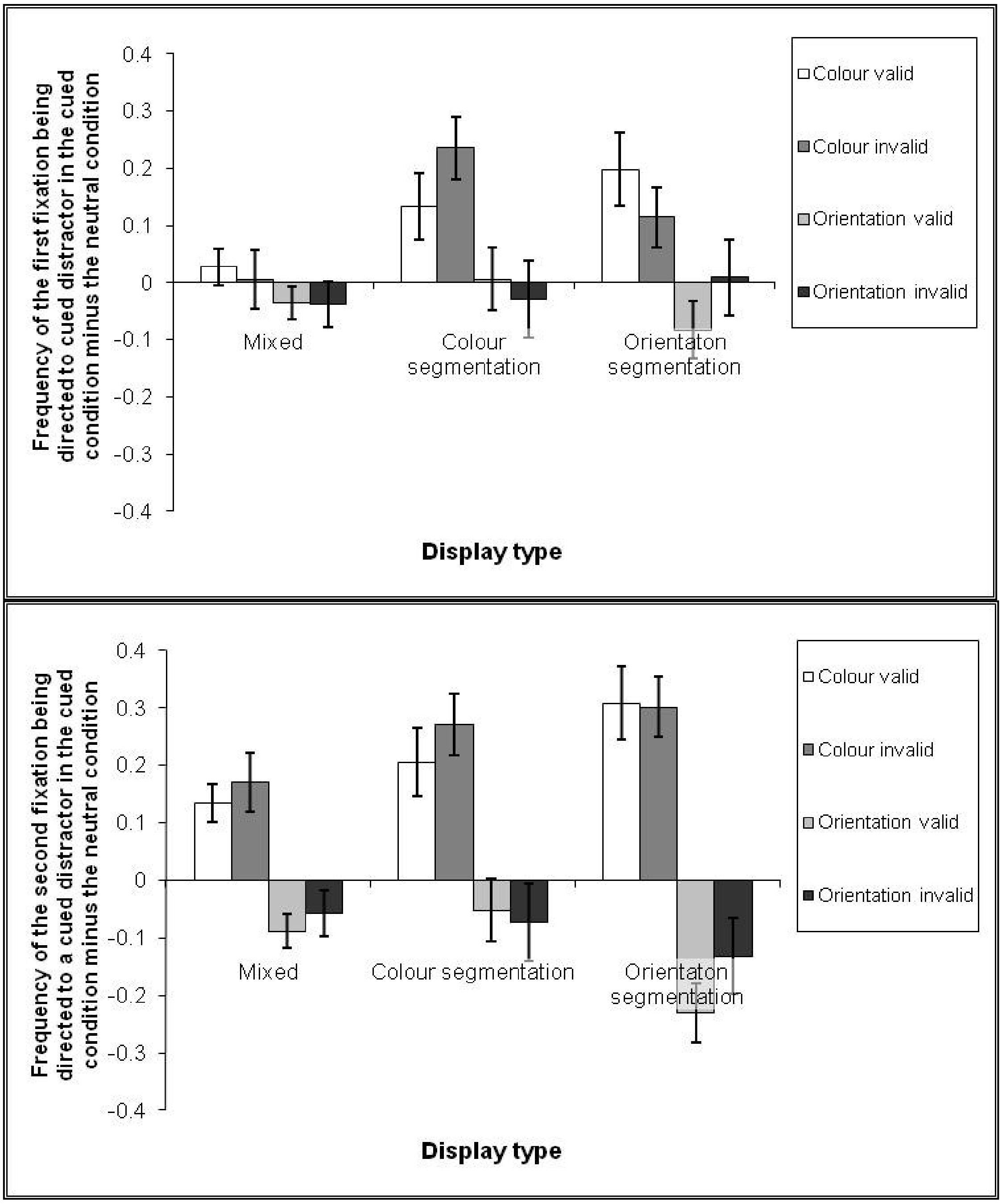

Figure 6.10. Means (+/- one standard error) of the mean frequency of first and second fixations being directed to a cued distractor in the cued condition minus the corresponding data in the neutral condition, in Experiment 6.3. The data were adjusted for chance and were separated by cue type, cue validity and cue dimension.

In the Mixed condition, analysis of the second fixation data revealed only a main effect of cue dimension ($F(1,18)=42.3$, $p<0.001$, partial $\eta^2=0.702$). There was an increase in the frequency of a fixation being directed to a cued distractor following colour cues (a positive effect of 0.152) compared to a decrease following orientation cues (-0.072). Analysis of the Colour and Orientation segmentation data showed a reliable main effect of cue dimension ($F(1,18)=81.9$, $p<0.001$, partial $\eta^2=0.82$). Colour cues increased the number of second fixation to cued dimension (a positive effect of 0.271) compared to orientation cues which decreased this frequency (a negative effect of -0.122). T-tests reflected that, while colour cues increased fixations to cued distractors compared to baseline ($t(18)=10.561$, $p<0.001$, one-tailed), fixations to cued distractors were significantly reduced on orientation-cued trials ($t(18)=-5.08$, $p<0.001$, one-tailed). There was also a display type x cue dimension interaction ($F(1,18)=12.8$, $p=0.002$, partial $\eta^2=0.415$). The negative effects (reducing fixations relative to baseline) following orientation cues were larger when the target and local distractors differed in orientation compared to when they differed in colour (Orientation segmentation vs. Colour segmentation: a difference of 0.118, $p=0.005$), while there was no difference between the positive effects from colour cues (a difference of 0.067, $p=0.178$).

6.3.4: Discussion

The RT data indicate a stronger effect on search following colour cues compared to orientation cues when adjacent distractors differed in both colour and orientation (in Mixed displays), while this disappeared when local distractors were grouped by the same feature (Colour and Orientation Segmentation displays). The differential pattern of cueing suggests that global grouping is stronger following colour cues, while local grouping and segmentation are equally efficient and equally modulated by colour and orientation cueing (equating performance with colour and orientation cues with the colour and the orientation segmented displays).

A complementary pattern of cueing effects was evident in the eye movement data. Validity effects were evident at first fixation – valid cues increased target-fixations, invalid cues reduced this frequency. However, this was only evident on homogeneous displays when the target differed from local distractors in orientation. In the remaining display conditions, cueing effects only affected second fixations. However, as with first fixations, validity effects were again stronger on homogeneous trials when target and distractors differed in orientation compared to when they differed in colour, with lesser effect evident on heterogeneous displays (the Mixed condition). The stronger and earlier cueing effects (from both types of cue) suggest that cues enhanced the segmentation of the target from adjacent stimuli when they differed in orientation within a colour-defined subset to a greater degree to when the local disparity was in the colour dimension. However, the differences between the effects on fixating the target in the two display types should be assessed with some caution. In the neutral baseline condition (Experiment 5.2), there was a bias towards fixating a target differing in colour to local distractors (Colour segmentation condition) compared to when the target-distractor differed in orientation (Orientation segmentation condition). Therefore, the effects of cueing in this condition may have been reduced due to the existing raised frequency in the baseline, perhaps creating an artificial relative increase in cueing effects in the Orientation segmentation condition.

As in Experiments 6.1-6.2, colour cues biased both first and second fixations not directed to the target towards distractors with the same colour as the cue, while fixations following orientation cues reduced the number of fixations to distractors matching the cue feature. Although colour cues operated as expected, directing search to matching search items, orientation cues did not, reducing fixations to the cued distractors relative to baseline. Following similar behaviour in Experiment 6.2 (in which distractors were distributed randomly), two proposals were made to explain the effects of orientation cues in that data. Both hypotheses assume that the search stimuli were preferentially grouped by colour (see Chapter 5). First, it may be that differential processes occur whether the target and cue match (valid orientation cues) compared to when they do not (invalid orientation cues). On valid cues, target colour is coded (perhaps by covert attentional processes) and search is therefore directed to stimuli matching this colour (not matching the orientation of cue). When cue and target orientation did not match, it may be that the colour disparity between target and an opposing colour group offered stronger guidance than the invalid cue (e.g., Experiment 5.2). Search would therefore be guided to stimuli in this subset and these items did not match the cued orientation. An alternate proposal is that participants create a mental image of the target from the cue (Soto & Humphreys, 2009). Search may then be preferentially guided by the colour associated with this image (cf., Huettig & Altman, 2005), rather than its orientation.

The current data demonstrated a stronger negative effect (reducing fixations to cued distractors, relative to baseline) from orientation cues when the local distractors and target also differed in orientation, compared to when they differed in colour. This bias indicated that the effects of orientation cues benefited when a local disparity in this dimension was present, while the effects were reduced when there was a local colour disparity. Search, therefore, is unlikely to be directed to uncued stimuli via an internal target template. Such processes should be unaffected by the nature of the display as they would occur prior to search. Perhaps the bias from orientation cues towards uncued distractors was due to local effects based on target-colour? The effects of valid orientation cues increased when the target and local distractors differed in orientation, suggesting that target-colour directed search to the uncued distractors. However, it would be expected that the effects of invalid orientation cues would be larger when the target and distractors differed in colour. Following invalid cue information, the strong colour signal should have directed search to uncued distractors. The data did not reflect this. It may be that cueing effects to this display type were reduced due to an existing bias towards fixating distractors adjacent to the target in the neutral baseline (see Experiment 5.2).

Taken together, the RT and the eye movement data indicate differential effects following orientation and colour cueing, with orientation cues affected by local disparities within that dimension while colour cueing operates at a more global level.

6.4: General Discussion

I have reported three experiments reflecting the effects of pre-cueing the likely feature of a conjunction search. Behavioural and eye movement measures were recorded, with cueing effects calculated by comparing performance on cued trials with those on neutral trials where no predictive information was available (for details see Chapter 5). In Experiment 6.1, the distractor ratio was varied and I compared how the effects of cueing attention to the likely colour or orientation of the target changed depending on the number of stimuli matching the cued feature. Valid cue information facilitated search (a benefit), relative to the neutral baseline, while invalid information slowed search (a cost). In addition, the relative effects of cueing the colour or orientation of the target differed depending on the display type. On RTs, benefits and costs from colour cues increased when participants were cued to attend to the larger group. Here the cue may counteract the bottom-up bias to attend to the smaller group.

Effects from orientation cues increased when participants were cued to attend to the smaller orientation group. This may again reflect the cue counteracting the bias to attend to the smaller colour group, which would not contain an orientation-defined target.

The eye movement data suggested that colour cues enhance the global grouping of stimuli into colour-defined groups, directing attention towards the cued subset. Orientation cues, on the other hand, tended to be less effective on directing fixations to targets, and they could even lead to fixations being directed away from stimuli sharing the cued attribute. I argue that this arose because participants may code the colour of the target which directed fixations to distractors within a colour-defined group whose members differ in orientation from the cue.

Experiment 6.2 used trials with equal distractor ratios, comparing the cueing effects from visual and verbal cues at long durations. There was little difference between the effects of visual and verbal the different types of cue on RTs and eye movements, although the effects of cueing found in Experiment 6.1 were largely increased following a longer duration cue. Comparisons of cueing effects on RTs across Experiments 6.1 and 6.2 also suggested that, with larger cue durations, it became more difficult to disengage attention from incorrectly cued distractors, particularly following invalid colour cues. In Experiment 6.3, I compared the effects of cueing on search with heterogeneous and homogenous (mixed and segmented) groups of distractors. There was stronger modulation of RTs from colour cueing compared to orientation cueing only in heterogeneous trials, suggesting that colour grouping following colour cues occurs on a global scale while suggesting that guidance mechanism following orientation cues occurs at a more local level (when the local items grouped). The eye movement results indicated a similar dichotomy.

Effects of orientation cues, evident when there was there was an orientation disparity between target and adjacent distractors, were markedly reduced when there was a local colour disparity signal. Conversely, the parsing of stimuli into colour-defined groups following colour cues was unaffected by the spatial relationship between stimuli.

6.4.1: Top-down effects interacting with ratio effects

Previous studies have shown that the distractor ratio effect, where RTs for a conjunction search are shorter on trials with uneven distractor ratios, to be relatively unaffected by top-down processes. Sobel and Cave (2002) found that instruction to restrict search to a particular feature (e.g., colour) only affected the search pattern across distractor ratios when the discrimination within the guiding dimension was easier relative to the complementary dimension (e.g., orientation). Our previous research (see Anderson et al., 2010) examined the effect of top-down processes on small-group search where the discriminability within each dimension had been equated. Using a similar methodology to Experiment 6.1, a stronger modulation from colour cues compared to orientation cues was evident regardless of the number of stimuli matching the cue feature. Cue validity did vary with distractor ratio, however, with a reduced cost of invalid cueing when there were unequal distractor ratios. That the effects of colour and orientation cues varied with distractor ratio in the current research can only be attributed to differences in methodology. The current display was less dense with fewer stimuli (to allow accurate eye-tracking) with a corresponding reduction in the variation in distractor ratio. Sobel & Cave (2002) found the ratio effect was more pronounced the denser the display. This suggests the modulation by top-down processes found here was evident only due to a reduced stimulus-stimulus interactions, compared to Anderson et al. (2010), and therefore reduced bottom-up guidance towards searching smaller group of stimuli (see Chapter 7 for further discussion).

Top-down cueing to targets was more effective with colour than with orientation cues, at least in terms of the directing of eye movements to targets. Here we can think that colour cues would operate in conjunction with bottom-up grouping and parsing into colour groups. Orientation cues were effective to the extent that they increased detection of an orientation disparity within colour-grouped displays with uneven ratios of distractors (Experiment 6.1).

The argument for early effects of colour grouping here fits with the argument that grouping by colour is fast acting (150ms; Braithwaite, Humphreys, Hulleman, & Watson, 2007) and analysis of the neutral baseline used here suggested an early bias towards fixating a minority colour-subset of distractors (see Chapter 5). Orientation cues, then, may enhance the detection of a disparity within the colour-defined groups. Previously, Hodsoll & Humphreys (2005) showed that a benefit for a target in a different orientation category to distractors arose only when participants had prior knowledge of the target's category. They proposed that the unique benefit following the cue was due to participants monitoring the categorically distinct channel defining the target. In the current studies, participants would therefore be set to detect particular differences in orientation within the colour-grouped stimuli (see Friedman-Hill & Wolf, 1995). The strength of the disparity signal may vary (see Figure 6.1), with this reflected in increased guidance towards fixating the target.

Extending this hypothesis into Experiment 6.3, I would expect greater effects on target-fixations following orientation cueing when the target differs in orientation from the adjacent stimuli. Smaller effect should be when colour was the dimension segmenting the target from neighbouring distractors (adjacent stimuli shared the same orientation). This proposal is in agreement with the data (see Figure 6.10).

6.4.2: Visual vs. verbal cueing

Experiment 6.2 showed few differences between the effect on eye movements or RTs from visual and verbal cueing, when the cue stimuli were presented for long durations and the ratio between distractors was balanced. This suggests that participants hold the information from the cue in a relatively abstract manner and that this information influences the deployment of attention during search. Soto and Humphreys (2007) showed that information unrelated to the search target retained in memory affected search speeds whether the information was presented as a stimulus or a verbal description of a stimulus. They proposed the effects were due to conceptual matching between the information in working memory and the search display. The long durations of the cues in Experiment 6.2 could also allow the creation of visual representations of the images of the targets. For example, Moores et al. (2003) found that facilitation effects from cueing spread to representations semantically associated with the cue item (e.g., a ‘motorbike’ cue speeds detection of a crash helmet), suggesting the facilitation effects occurred at a conceptual level. Moreover, Huettig and Altman (2005) found that participants tended to fixate an object on hearing its name. This tendency also spread to other items semantically associated with the object, leading the authors to suggest that the interaction occurs between visual representations of the objects. Comparisons between Experiments 6.1 and 6.2 indicated stronger effects following longer cues, offering some confirmation that the extra time afforded to participants allowed development of the cued target template from the cue.

6.4.3: Conjunctive search

One difference between colour and orientation cueing that was also magnified by a longer cue is which type of distractor was fixated following each cue dimension. Following a shorter cue (200ms, Experiment 6.1) there was strong guidance from both valid and invalid colour cues towards fixation distractors matching the colour of the cue, with this effect present regardless of the number of these stimuli. Following orientation cues, however, the largest effect on eye-movements was following invalid cues when the distractor ratio was balanced, with fixations more likely to be to distractors not sharing their orientation with the cue. Our proposal here is that participants selected a colour-defined group, within which the target differed in colour. Due to the salience of the target attention (and eye movements) may be re-oriented to the other colour group, decreasing the likelihood that distractors sharing the orientation of the target were selected.

When cues were presented for longer (1200ms) and the distractor ratio was balanced (Experiment 6.2), colour cues guided fixations as previously, directing attention to those matching the cue feature. However, with long durations both valid and invalid orientation cues directed fixations to those not sharing the cue feature/sharing the colour that matches the cue feature, biasing both first and second fixations in this manner. It is possible that there was some initial priming of attention from the orientation cue, which was effective when there was a short interval between the cue and the search display, but not when there was a longer interval. At the longer interval, therefore, it may be that following valid orientation cues there was covert processing of the colour of the target, with search then guided by this feature. This bias may be less apparent on trials with uneven distractor ratios (see Fig. 6.1a, Fig.

6.1c) as a strong bias towards smaller groups of distractors may overrule attentional selection based even on cued orientation information.

Recent studies have provided evidence of search guided by a conjunction of features. Hannus et al. (2006) suggested that filters set to a particular combination of features are used during conjunction search. They employed a pre-cue to indicate which stimulus in the following feature-defined or colour-orientation conjunction search participants should search for and fixate. The discriminability of the two dimensions had been balanced so that in a feature-defined search there was no difference in the probability of a saccade directed to a stimulus with the cued colour or orientation. However, in the conjunction search there was a large decrease in the likelihood of the fixation directed to a stimulus with the cued orientation, while there was no change for the colour dimension between the two search types. Hannus et al. proposed that conjunction channels are chromatically sensitive channels used to detect orientation differences in single feature search, citing that orientation-selective neurons have been shown to be as selective to colour as non-oriented neurons (von der Heydt, Friedman, & Zhou, 2003). Takeda, Phillips and Kumada (2007), moreover, found search to be more efficient when distractors were defined by the same conjunction of features than when distractors were made up of random conjunctions of the same features. They argued that distractors can be grouped by a conjunction of features, with search guided by a conjunctive 'feature' in a similar manner as any other feature.

There is evidence in the neurological literature for specific deficits during conjunction search not evident during search for a target defined by a single feature. Patients with unilateral neglect (e.g., Esterman, McGlinchey-Berroth & Milberg, 2000; List et al., 2008) and Balint's syndrome (bilateral damage to the dorsal –

occipital-parietal, processing stream; e.g., Robertson, Treisman, Friedman-Hill, Grobowecky, 1997) have shown difficulties searching for conjunctions as have observers with Alzheimer's disease (Tales et al., 2002), which can impinge on the parietal cortex. Explanations have focused on problems in binding the features that form the target, with illusory conjunctions arising when the process misfires (see Robertson, 2003, for a review). However, the findings could also reflect damage to neurons specifically tuned to detect conjunctions of features (see Hannus et al., 2006). In the present case, an orientation cue could activate conjunctive representations that group by having the cued colour and a shared orientation. In the present conditions this may not be useful because the same-colour group with the target's orientation would not contain the target (on valid trials). This may then lead to fixations being directed away from the cued orientation, to the other colour group.

6.4.4: Fixation accuracy

All the above effects should be taken with some provisos. Defining the item nearest to fixations as the stimuli being processes during a particular eye movement may have not been optimal. The accuracy of the fixation data (e.g., how far the fixation location was from the nearest search item) for this chapter did not differ from that outlined in Chapter 5 (see 5.1.3). The locations of fixations recorded during the experiments rarely overlapped with the nearest search item. As with prior research (e.g., Findlay & Gilchrist, 1997; Zelinsky et al., 1997), first fixations were directed to the space between adjacent stimuli with second fixations then directed closer to a particular search item. It may, therefore, be that initial eye movements cannot be attributed to the closest stimuli. Instead, several stimuli may have been processed (Zelinsky, 1996) before a more accurate movement is made. Further to this, the spatial accuracy for the eye tracker may be inadequate for the dimensions of the stimuli used, as the spatial accuracy (0.5°) was half the length of a search item. Therefore, fixations detected as landing on a stimuli (although these were few in number) may have been inaccurately localised.

Despite these factors, the majority of first fixations (less than 95%) were within the penumbra an item with this distance decreasing at second fixations. This distance decreased at second fixation, suggest that the system was sensitive to the guidance developing during search. While acknowledging these issues, I suggest it is reasonable that the data presented here reflect a combination of covert and overt processes and can be analysed to interpret the pattern of visual processes.

6.4.4: Conclusion

This series of studies offers extensive evidence for differential effects on reaction times and eye-movement behaviour following cues indicating the likely colour or orientation of a conjunction search. Strong effects of colour grouping and cueing were evident in all the experiments, and colour grouping appeared to precede effects of top-down orientation cueing. In addition, the data indicated that colour cueing operates on a global level, parsing the display into colour-defined groups of stimuli, even with spatially mixed colours. In contrast, processing following orientation cues appeared to operate more locally, enhancing segmentation/grouping processes primarily between adjacent stimuli (Experiment 6.3). I conclude that colour and orientation cueing effects differ not only in their quantitative effects but also qualitatively in how they operate.

CHAPTER 7

General Discussion

7.1: Introduction

The five series studies presented in this thesis were all concerned with the effect on behaviour of advanced knowledge about the target of a difficult search task. Specifically, I compared the effects of pre-cueing the colour and orientation of a target defined by a conjunction of these two dimensions. Two possible targets were used which allowed the examination of processes following valid and invalid cueing information as well as reducing stimulus-driven guidance effects in uncued trials on search compared with only presenting a single target. Prior the cued experiments, the targets were balanced for search efficiency within the colour and orientation dimensions to control for stimulus-driven bias towards search defined within each dimension (e.g., Bacon & Egeth, 1997; for details see Chapter 2).

7.2: Summary of Thesis

The first experimental chapter (Chapter 2), outlines how the targets and distractors used later in the thesis (Chapters 3-6) were first balanced for search efficiency within the colour and orientation dimensions. Therefore any cueing bias between dimensions can be attributed to top-down rather than stimulus-driven processes. Chapter 3 then showed that, relative to neutral, uncued trials, correct cue information (valid trials) about the target facilitated search while reaction times (RTs) were longer on invalid trials (a 'validity effect') There was, moreover, a larger overall effect on attention from colour cueing compared to orientation cueing (cf. Müller, Reimann, & Krummenacher, 2003). However, there was no difference between the effects of colour and orientation cueing on search efficiency; valid cues improved efficiency, relative to the neutral condition, while invalid cues led to a decrease. There were robust validity effects when the ratio between distractors was manipulated (cf. Sobel & Cave, 2002), with stronger effects again evident following colour cues. The colour advantage did not vary with the number of items matching the cue, although the effects of both colour and orientation cues diminished when cueing either the smaller or larger subset compared to when the ratio was balanced. This was particularly evident in a reduced cost on invalid trials. The stronger effect from colour cues remained when the response was changed from a present-absent to a search-irrelevant decision, ruling out a response-level explanation for the colour advantage (see Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997). Similarly, stronger effects from colour compared to orientation cues were evident whether the cues were visual or verbal, indicating that the asymmetry was not due to differences in priming from the physical nature of the cues (cf. Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). The pattern of cueing effects were therefore interpreted to reflect participants preferentially searching the cued group of stimuli, with a benefit early in search from colour cues in the segmentation of displays into colour-defined groups compared to similar processes following orientation cues.

While the effects of visual and verbal cues were matched at long cue durations (Chapter 3) priming from the physical nature of visual cues may still play a role. In Chapter 4, the cue duration and featural relationship between the cue and target were varied. When the physical nature of the cue matched their predictive information (e.g., a green patch preceding a green vertical target), the colour advantage over orientation was relatively robust across cue duration (100-1200ms), diminishing only on invalid trials. When non-predictive features were introduced to cues (e.g., a green horizontal/vertical cue predicting a green vertical target, although its orientation was non-predictive, matching the target only at chance) there was a larger effect from the colour of the cue when was it non-predictive compared to when orientation was the non-predictive feature. This effect of non-predictive cue colour occurred even at short cue durations and remained when the colour of the cue was anti-predictive (matching the target on 20% of trials). The effect was reduced when the predictive feature (in this case orientation) did not match the target. The findings suggest either that the colour of the cue was automatically processed (cf. Soto & Humphreys, 2009) and reduced with time, or that all cue information was rejected once the predictive information had been identified as invalid. Whatever the processes involved, the data offered evidence that priming from visual cues play a part in the effects from visual cues.

The final two experimental chapters replicated the methodology of Chapter 3 to a great extent. However, as well as detailing RTs, eye fixations made during, neutral uncued (Chapter 5) and cued (Chapter 6) trials were recorded, offering immediate information about the search process rather than just overall measures of search efficiency. On neutral trials, it should be noted, participants did not know which target was likely to be on the next trial, thereby reducing top-down guidance towards items sharing a feature with the target (e.g., Kim & Cave, 1995, 1999). The neutral, uncued data reflected a robust bias towards smaller subset search, with shorter RTs at uneven distractor ratios (e.g., Sobel & Cave, 2002), as well as an increase in target fixations. Initial fixations were more likely to be directed towards the distractor type in the minority (Williams & Reingold, 2001), with subsequent eye movements indicating stronger grouping between same-coloured stimuli. When the spatial relationship rather than the ratio of distractors was varied, however, the data showed initial fixations to be guided towards the target when the local target and distractors differed in colour. Search was then guided to the distractors adjacent to the target at second fixation. The findings were interpreted as evidence that in conditions of reduced top-down guidance there is a stronger salience signal from stimuli differing in colour, whether this signal was from an isolated target or a minority colour group. The latter suggests more robust grouping from stimuli sharing the same colour than the same orientation.

The effect of colour and orientation cueing on eye movements and RTs indicated differing mechanisms (Chapter 6). The influence of cues on RTs and eye movements varied depending on the distractor ratio, cue duration and the spatial relationship between distractors. Following Chapter 5, it was asserted that the stimuli were preferentially grouped by colour, regardless of the cue. Guidance from the cues therefore operated within these colour-groups. Colour cues facilitated the parsing of stimuli into colour-defined subsets. Orientation, on the other hand, guided attention by enhancing the local orientation disparity within these subsets. Similar patterns of effects were evident following both visual and verbal cues and were increased following longer cue durations, suggesting that representations of the cueing information were able to develop following longer cues (see Chapter 3). These findings indicate that the advantage for colour over orientation cues may be due to stronger initial grouping between stimuli sharing the same colour, allowing stronger guidance from prior knowledge about the colour of the target to occur within these colour groupings. Guidance from orientation cues, however, was not as efficient at directing search within items grouped by colour.

7.3: Grouping vs. Segmentation

This thesis makes substantial progress towards understanding the mechanisms behind featural cueing of a conjunction search target. Stronger guidance was evident from cueing the colour of the target compared to cueing its orientation. Given that the targets used were balanced for search efficiency within both orientation and colour dimensions, it was proposed that the difference in cueing effects was due to diverging top-down processes. However, the findings led to dissimilar interpretations of this asymmetry.

The data from the two experiments where cueing effects were pitted against subset search (Experiments 3.2 and 6.1) reflected contrasting patterns. In Experiment 3.2, the effects of colour and orientation cues on RTs were additive across the size of the distractor subset cued. The validity effect – valid cues facilitating search, invalid slowing search – of both types of cue decreased on trials with uneven ratios, largely reflected by a reduced cost from invalid cues on these displays (see Fig. 3.5). However, no variation in the effects of colour and orientation cues was observed. As the advantage was not due to differences at response-level processes (see Experiment 3.3), these findings were interpreted to indicate an early advantage following colour cues in the efficiency of segmenting stimuli into colour-defined groups.

The effects from colour and orientation cues on RTs in Experiment 6.1, however, varied depending on the number of distractors matching the feature of the cue. Colour cues were reduced when cueing the small group compared to when the large colour group was cued, while the pattern was reversed for orientation cues. The stronger modulation following colour cues (see Chapter 3) was evident when the distractor ratio was balanced or the large group was cued. However, a similar colour advantage was absent when the cued feature matched the minority feature in the display (see. Fig. 6.2). The eye movement data from the uncued condition used as baseline for Chapter 6[14] indicated that fixations were preferentially directed towards colour-defined subset of stimuli (see Chapter 5). On cued trials, therefore, it was proposed that search items were initially grouped by colour, irrespective of the cue. Guidance from colour cues may then involve facilitating the parsing of the stimuli into groups and directing search towards the relevant subset. The reduced guidance from orientation cues would be due to orientation-directed search having to operate within a stimulus array already grouped by colour.

So how do we account for these two interpretations? One, where segmentation of items into groups is deemed more efficient following colour cues; the alternative, where initial stronger grouping between stimuli sharing the same colour allows a stronger guidance from colour cues? It should be highlighted that there were methodological differences between the two experiments. To enable accurate measurement of item-fixations in Chapters

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[14] Similar eye movement data was unavailable for the neutral, uncued condition used in Chapter 2.

5 and 6, the number of array items was reduced relative to Experiment 3 (where eye movements were not recorded), while the display area was unchanged. The spatial density of the search display was therefore reduced in Experiments 5 and 6, a factor that has been shown to weaken the bias towards ‘subset search’ (e.g., the facilitation of search when a smaller group of distractors is present; see Sobel & Cave, 2002). As subset search is thought to be stimulus-driven, guidance would be increased on displays with uneven distractor ratios due to an increased number of differences between neighbouring stimuli compared to when the size of subsets is balanced. The bias would thus be stronger in Chapter 3, due to the higher density of displays, than in Chapter 5 and 6, where the items were more disparate (Sobel & Cave, 2002).

There are therefore two possible proposals. First, that the mechanism behind the stronger effect of pre-cueing the colour of the target depends on the density of the stimuli being searched. When the items are tightly packed (Chapter 3), the colour advantage is due to more efficient segmentation into cued colour-defined groups compared to the processes following orientation cues. When the items are more spaced out (Chapters 5 and 6), the larger modulation of attention following colour cues is linked to stronger grouping between same-colour stimuli compared to orientation stimuli prior to the cue. Colour cueing processes therefore benefit from guiding search within colour-groups, while orientation cues are less efficient at operating within the same parameters. Second, that stimuli are preferentially grouped by colour, however these grouping processes may require the stimuli to be segmented for this advantage to be evident, particularly when the stimuli are in close proximity. In spatially dense displays (Chapter 3), colour cues may facilitate the parsing of stimuli into colour-defined subset more efficiently than orientation cues. Segmentation often occurs at the boundary of items with properties that tend to group together (Duncan & Humphreys, 1989), so it seems suitable that the processes should be complementary. For more disparate displays (Chapters 5 and 6), the segmentation may not be required as grouping processes were already robust in the absence of cues (see Chapter 5). The second proposal suggests a more consistent mechanism, however more research is required to make more definitive conclusions (see 7.6).

7.4: Attentional Models

It is worthwhile assessing the implications from the research in terms of functional theories of visual search. Only certain models are addressed, however, as the differential effects of cueing are less relevant to other theories described previously (e.g., Dimensional Action Model).

7.4.1: Guided Search Theory. As outlined previously (see 3.5.2), the Guided Search Theory account (GST: Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) accommodates the interaction between top-down cueing and bottom-up, stimulus-driven processes proposed in the segmentation hypothesis in Chapter 3. GST posits an initial preattentive parallel stage of visual processing where basic visual features are coded independently in distinct retinotopic ‘feature maps’. Activation within the feature maps reflect both the bottom-up saliency of the stimuli (e.g., generating by local differences between elements) and top-down cueing (pre-activation of the maps by foreknowledge of the target). Within this framework, pre-cues in our studies would increase the activation of the stimuli sharing the cued feature, facilitating their selection over items not subject to top-down cueing. As a consequence, segmentation of the stimuli, and selection of one group of elements based on the cued feature, may be faster relative to when the cue is neutral. On a valid trial, search would be facilitated as the target will be a member of the selected group. This comes at the cost of performance on an invalid trial, when a distractor group will show speeded selection and attention may need to be disengaged in order for the target to be subsequently selected. To explain our observed differences between the top-down cueing of colour and orientation, it was proposed that the gain on the top-down input into the colour feature map should be raised, thereby increasing the top-down biases towards segmentation into a winning and losing group. This facilitated segmentation following colour cues would generate an overall RT advantage even if there is subsequently serial selection within the ‘winning’ group of items. On the other hand, to bring GST into line with the stronger grouping by colour (see Chapter 5), the activation output from the particular feature maps of stimuli with the same colour value could be weighted more than the complementary activations for stimuli sharing the same orientation, thereby guiding attention preferentially to the location grouped by the same colour. The two differing biases could work in conjunction, moreover, combining to preferentially direct search towards items matching the cued colour compared to those sharing the orientation with the cue.

7.4.2: Attentional Engagement Theory. The bottom-up salience of items within GST is driven by the similarity of local stimuli. Therefore, increased salience for items grouped by colour is more difficult to account for within its framework compared to that of the Attentional Engagement Theory (AET, Duncan & Humphreys, 1989, 1992) which includes perceptual grouping as a fundamental process. AET is a two-stage model in which there is preattentive grouping of stimuli followed by a matching of the representations to a template of the target. Pre-cueing the target will increase the ‘pertinence’ of matching distractors, enabling them to win the competition for selection (cf. Bundesen, 1990; Heinke & Humphreys, 2003; for similar, more formal accounts). Cueing effects simply reflect which group is selected first. During the initial process items are segmented into subsets grouped by a shared feature (e.g., colour or orientation). Therefore, the benefit from colour cues, compared to orientation, may appear to occur due to stronger grouping between stimuli with the same colour (Chapter 6). This colour-defined ‘unit’ would then have an advantage in the competition for selection. Moreover, colour cues could also be seen to facilitate the segmentation of same-colour items into perceptual units (Chapter 3) compared to orientation cues, again leading to a benefit in gaining selection for stimuli matching the cue colour.

7.5: Eye-tracking accuracy

The accuracy of the set-up used to measure eye movements during Chapters 5 and 6 can be criticised with a knock-on effect as to the validity of the interpretation of the fixation data. First, using an eye-tracker that is only accurate to a visual angle of 0.5° when the stimuli used are only 1° in size and 2.4° apart allows for little sensitivity when determining whether the actual search item was fixated or not. Although the data presented in 5.1.3 indicate that second fixations were closer to search items than initial eye movements, further examination of search patterns should be undertaken with an eye-tracker with better spatial accuracy (e.g., a Dual Purkinje set-up). Increasing the size and spatial lay-out of the search items would also improve the methodology, however this may interrupt the very grouping processes being measured (see 7.3). Second, attributing processing at first fixation to the nearest item may not be advisable. Initial eye movements have been shown to be programmed to a location between stimuli (e.g., Zelinsky, Rao, Hayhoe, & Ballard, 1997). In the current study, first and, indeed, second fixations were directed to the locations adjacent to search items. However, these locations were within the penumbra of the nearest item (e.g., closer to the stimulus than half the average distance between neighbouring stimuli). So, while the fixations may not be directed to the items themselves, I feel justified that the items nearest to the eye movements were preferentially processed.

7.6: Future Research

While the segmentation and grouping accounts of the advantage from colour vs. orientation cues are consistent with models of attentional deployment, it would be preferential, if possible, to remove the stronger grouping of items by colour evident in the displays used Chapters 5 and 6. All the current studies involved targets that had been balanced for discriminability within both the colour and orientation dimensions (Bacon & Egeth, 1997; see Chapter 2). However, further examination of cueing processes should involve the matching of the grouping of stimuli by colour and orientation. One paradigm that would allow the comparison, and therefore equating, of grouping by particular features would be preview search, in which a subset of search items is presented prior to the target-containing subset of items. Participants have been shown to inhibit the positions of preview items if they are grouped by colour (Braithwaite, Humphreys, & Hulleman, 2005) or orientation (cf. Hodsoll & Humphreys, 2007). As a consequence, search within the preview condition is faster compared with when all items are presented simultaneously. Instead of balancing targets using feature-defined search as here, further research could adjust the stimuli so that the preview effect of stimuli with the same colour matches the similar effect from stimuli sharing the same orientation. In conjunction with equating these grouping processes, further studies should use more accurate eye tracking (see 7.5) and may also consider intentionally manipulating the spatial density of search items (cf. Sobel & Cave, 2002). Considering how cue effects varied with this factor (Chapter 3 vs. Chapter 6), recording the effects of cues on RTs and eye movements during search displays differing in items per spatial unit would offer an indication of how these bottom-up factors influence colour and orientation cueing, as well as any underlying grouping processes.

A further extension of the current set of studies would be to investigate how the benefit from using colour cues compared with other visual dimensions. While its dominance over orientation is in little doubt, generalising this advantage would add weight to the findings. For example, comparing colour pre-cues with prior information based on motion, size, or luminance may allow the development of a top-down hierarchy of visual perception, with features ordered by strength of top-down guidance associated with them. Extending the methodology into more socially relevant environments – such as searching for a face in a crowd – would also be beneficial. Cells coding colour and orientation are easy to spatially separate, indeed there is some evidence that certain cells process features from both dimension (e.g., Gegenfurtner, Kiper, & Fenstemaker 1996; Ts'o & Gilbert, 1988). Introducing a different dimension (e.g., motion) or using faces as search items, would facilitate the use of scanning techniques, such as fMRI, in mapping out differences in the neural pathways involved in the guidance from different types predictive information.

Another neurological avenue of research would be to use electroencephalography (EEG) to detect on-going brain activity during cued search tasks. It would offer a time-sensitive measure of the brain states that mediate the tasks involved. An adapted version of the methodology outlined in the current thesis could be used to contrast colour and orientation cues in visual search tasks whilst EEG-event related potentials (ERPs) are recorded. The so-called N2pc component of the ERP response – the difference in activity across the two cerebral hemispheres when a target stimulus falls in the contralateral relative to the ipsilateral visual field (Woodman & Luck, 1999) – would be of particular interest. This component is largest over posterior visual areas and is generally interpreted as reflecting the strength of an orienting response to the contralateral side of space. The behavioural data from this thesis has shown that colour cueing modulates attention to a larger degree than orientation. It would be revealing whether a similar dimensional difference occurs for the N2pc and the time-line of this variation.

7.6: Summary

In sum, the present thesis demonstrates contrasting effects from colour and orientation pre-cueing of a search target, even when the discriminability of stimuli had been balanced within each dimension. Both types of cues show validity effects, whereby valid information facilitates search while invalid cues slow search. Colour cueing, moreover, leads to a greater modulation of attention. The difference between the effects colour and orientation cues was not due to response-level processes (cf. Cohen & Feintuch, 2002) as it remained when any direct link between cue and response had been removed (e.g., a compound task). The mechanism behind this bias may involve an advantage in the top-down efficiency of segmenting stimuli into colour-defined groups at an early level of processing. Search would then be directed towards the cued subset. The segmentation and consequential guidance following orientation cues was less efficient, however. Alternatively, the benefit from colour cues may be due to stimulus-driven processes, with stronger grouping between items with the same colour. Colour cues would therefore be more efficient in directing search within this grouped framework while the guidance from orientation cues would suffer. The segmentation and grouping processes may be working simultaneously, however, with the relative strength of each dependent on the spatial density of the array. On tightly packed displays the grouping effects may only become evident after segmentation following a cue; however, the segmentation may not be necessary when items are more spread out. There was strong evidence of a significant role for effects from the physical colour of the cue that were absent on orientation-cued trials. This suggested that priming of the visual system from coloured cueing stimuli (cf. Kristjánsson, 2006) could explain the difference between colour and orientation cueing effects. However, the colour benefit remained following verbal cues presented for long durations. These finding suggest that, given time, a visual representation of the target develops following the cue that guides attention during search (cf. Moores, Laitti &

Chelazzi, 2003), with the properties of this representation affecting search behaviour (e.g., Soto & Humphreys, 2009).

Despite possible contradictions outlined above, our findings clearly reflect stronger modulation of search from pre-cueing the colour of the target compared with pre-cueing its orientation. As well as its impact on psychological models and other areas of research, these findings should also be taken into consideration in practical situations, such as in developing the lay-out of car dashboards, airplane cockpits or designing essential traffic or evacuation signage. In high-stress environments, where detecting a particular visual stimuli is vital, any advantage is beneficial. Using the stronger guidance available from colour information, therefore, would be advisable.

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