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Kevin Dent, Glyn W. Humphreys, Xun He, Jason J. Braithwaite

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Surface-based constraints on target selection and distractor rejection: Evidence from preview search

Kevin Dent[1]

Glyn W. Humphreys[2]

Xun He[3]

Jason J. Braithwaite[4]

[1]University of Essex

[2]Oxford University

[3]Bournemouth University

[4]University of Birmingham

Corresponding author

Kevin Dent

Department of Psychology

University of Essex

Wivenhoe Park

Colchester

Essex

CO4 3SQ

+44 (0) 1206 83785

kdent@essex.ac.uk

Abstract

In preview search when an observer ignores an early appearing set of distractors, there can subsequently be impeded detection of new targets that share the colour of this preview. This “negative carry-over effect” has been attributed to an active inhibitory process targeted against the old items and inadvertently their features. Here we extend negative carry-over effects to the case of stereoscopically defined surfaces of coplanar elements without common features. In Experiment 1 observers previewed distractors in one surface (1000 ms), before being presented with the target and new distractors divided over the old and a new surface either above or below the old one. Participants were slower and less efficient to detect targets in the old surface. In Experiment 2 in both the first and second display the items were divided over two planes in the proportion 66 / 33% such that no new planes appeared following the preview, and there was no majority of items in any one plane in the final combined display. The results showed that participants were slower to detect the target when it occurred in the old majority surface. Experiment 3 held constant the 2D properties of the stimuli while varying the presence of binocular depth cues. The carry-over effect only occurred in the presence of binocular depth cues, ruling out any account of the results in terms of 2-D cues. The results suggest well formed surfaces in addition to simple features may be targets for inhibition in search.

Keywords: attention; visual search; 3-D surface; preview search; inhibition; negative carry-over

The visual environment presents the visual system with a great deal of information much of which may be irrelevant for the observer's current task. Flexible mechanisms of selection are required to ensure that behaviour is efficiently directed to the most relevant stimuli (see Allport, 1987; Neumann, 1987). The visual search task in which an observer must select a target item amongst a cluttered array of distractors has been an important tool for understanding these mechanisms of selection (see Chan & Hayward, 2013; Wolfe, 1998 for a reviews).

Observers may use salient differences in the features of targets and distractors to select relevant and reject irrelevant portions of search displays. Several features of stimuli may serve to guide search in this way: motion (e.g. McLeod, Driver, & Crisp, 1988), colour (e.g. Egeth, Virzi, Garbart, 1984), stereoscopic depth (e.g. Nakayama, & Silverman, 1986), and temporal differences in the onset of stimuli (Watson, & Humphreys, 1997). In the context of search there has been substantial debate concerning the relative importance of inhibitory (e.g. Treisman & Sato 1990) and excitatory (e.g. Wolfe, Cave, & Franzel, 1989) mechanisms in mediating feature-based selection in search. The current consensus is that excitatory processes directed towards potential targets are complemented by inhibitory processes directed against distractors (see Dent, Allen, Braithwaite, & Humphreys, 2012 b, for a review). The goal of the current paper is to further characterise the inhibitory mechanisms that contribute to selection.

Preview search and distractor suppression

Inhibitory processes in search and selection have been particularly well documented in the context of preview search, where temporal differences in stimulus onset provide the cue for selection (e.g. Jiang, Chun, & Marks, 2002; Theeuwes, Kramer, & Atchley, 1998; Watson & Humphreys, 1997; see, Watson, Humphreys, & Olivers, 2003 for a review). In the preview paradigm observers may effectively ignore an early appearing set of distractors in favour of a set of potential targets occurring at least 400ms later (e.g. Watson & Humphreys, 1997). There is good evidence to support a role for inhibitory mechanisms in excluding these early items from selection. For example, as a consequence of previewing a set of distractors observers are impaired at detecting otherwise salient probe-dots presented close to these distractors (e.g. Humphreys, Jung-Stallman, & Olivers, 2004). These selective costs for detection near distractors are not observed if the participant is not set to ignore the previewed items (e.g. Watson & Humphreys, 2000), or is engaged in a concurrent attentionally-demanding task (e.g. Olivers & Humphreys, 2002). Additionally, there is evidence that the preview benefit depends on limited capacity resources that may decay over time, such that only the first few deployments of attention are advantaged. (e.g. Al-Aidroos, Emrich, Ferber, & Pratt, 2012; Emrich, Ruppel, Al-Aidroos, Pratt, & Ferber 2008; Watson & Kunar, 2012). On balance the preview benefit is most readily explained by limited capacity top-down inhibition actively applied to the old distractor locations.

Although, Watson and Humphreys (1997) initially proposed that inhibition in preview search applied only to the locations of the stimuli, subsequent experiments have shown that other features of the rejected items may also be inhibited. Watson & Humphreys (1998; see also Olivers, Watson, & Humphreys, 1999) showed that when the old items were constantly moving and their locations continuously changing, participants relied to a greater extent on colour, only showing a preview benefit when the old and new items were different colours. Kunar, Humphreys and Smith (2003) also demonstrated that changing the colour of the old items during the preview period was detrimental to search only when the search items were moving. This greater reliance on colour information under conditions of movement can be explained as a switch from location based to colour based inhibition, specifically inhibition of a particular colour feature map.

Subsequent experiments have shown that colour inhibition can be implicated even in the case of static stimuli. Braithwaite and Humphreys (2003, see also Olivers & Humphreys, 2003) showed that a new target that shared colour with the previewed items could be very difficult to detect- the negative colour carry-over effect. Braithwaite, Humphreys and Hodsoll, (2003) showed that negative carry-over effects for colour could be generated even for bicoloured previews. It was not necessary that all early appearing distractors had the same colour, so long as there was a majority of items in one colour. For example, the preview display might have a red majority and a green minority (66% red to 33% green), with the subsequent search items biased in the opposite direction (33% red to 66% green). Despite an even ratio of red to green items in the final display, items carrying the old majority colour (red) remained very difficult to detect. Braithwaite and colleagues (Braithwaite, Humphreys, Hulleman, & Watson, 2007; Braithwaite, Humphreys, & Hulleman, 2005) have shown that initially in the preview period the old minority can be favoured over the old majority (see also Poisson & Wilkinson, 1992), and this bias may lead to greater inhibition of the old majority and less inhibition of the old minority, and as a result, unequal inhibition of the associated colours.

One question that has arisen in the context of the negative colour carry-over effect is the relative importance of inhibition of the feature values of objects and inhibition of groups of items defined by shared features. Certainly there is evidence supporting a contribution of spatial grouping processes to the preview benefit. Watson (2001) demonstrated a role for grouping distractors into spatial configurations in preview search. Specifically, the extent to which participants rely on colour when the old items undergo constant motion in preview search, depends critically on the type of motion involved. When the items abrubtly disappear at one end and then reappear at the other end of a screen the preview benefit is disrupted unless there is a colour difference. However, if the old items rotate around the centre of the screen such that they never disappear and reappear a robust preview benefit is obtained even for achromatic items. Watson (2001) suggests that under these circumstances the old items may be grouped into a spatial configuration and inhibited en-masse. Further evidence comes from a study by Kunar, Humphreys, Smith, and Hulleman (2003), which showed that the preview benefit was preserved in the face of abrubt changes in the location of the preview items so long as the spatial relations between the items was preserved. Osugi, Kumada, and Kawahara (2009) also concluded that the old items in preview search may be spatially grouped. Osugi et al., (2009) showed that probe detection could be impaired for probes presented inbetween adjacent old distractors, consistent with the inhibiton of grouped items including the empty space inbetween these items.

Does the negative colour carry-over effect really stem from direct suppression of the feature value of the majority old items? An alternative view is that there is colour-based grouping between the suppressed old items and the new target, and this makes the target difficult to detect. Braithwaite et al. (2003; see also Braithwaite, Humphreys, & Hodsoll, 2004; Braithwaite, et al., 2005) examined this issue by changing the colour of the old items coincident with the onset of the new items, under these conditions colour grouping between old and new items may be disrupted, yet the carry-over effect persisted. The colour change results support the idea that it is the feature value of the old items that is suppressed directly, rather than a colour based group. Specifically, in order to account for these findings Braithwaite et al. (2003; see also Braithwaite et al., 2007) recruit the notion of feature-map inhibition similar to that described by Treisman & Sato (1990).

According to Feature Integration Theory (FIT, Treisman, 1988) a feature map is a representational structure that codes the presence of a particular elementary feature throughout the visual field (although that location information may not be explicitly available for report). Features, may be understood as properties of individual items located at particular locations in space. A feature of an item may be measured and assigned a value. Typically, features are understood to be computed relatively early in visual perception and to have dedicated functional modules and neural hardware. According to FIT there are feature maps dedicated to specific feature values in several different dimensions (e.g. colour: red, green, blue; motion: upward, downward; orientation: upright, vertical). A feature map is an architectural component of the visual system, that may pre-exist external sensory stimulation, as such a feature map can be a target for attentional control. According to Treisman & Sato (1990) if a feature is known to be irrelevant (characterising only distractors) then activity arising in such a map can be suppressed, and this can lead to attention being directed away from distractor locations. According to Braithwaite et al. (2007) when a set of early appearing distractors is suppressed, there is also unavoidable and obligatory suppression of the colour feature map coding the majority colour. Thus new items that are also represented in this colour map suffer a disadvantage.

The colour change results of Braithwaite et al. (2003; 2004; 2005), argue that feature map inhibition is logically sufficient for the carry-over effect to occur. The goal of the current paper is to assess if this is the case. Braithwaite et al (2003; 2004; 2005) showed that carry over effects can occur when there is a history of shared features, but no current grouping between the old and new items. Here we investigate the situation where there is no history of shared features but there is a current spatially defined group. Do carry-over effects occur under these conditions? In order to create this situation we recruited stereoscopically defined slanted surfaces.

Stereoscopic Surfaces

Human behaviour takes place in a 3-dimensional world, relatively few studies have explored search and selection in the context of 3-D stimuli, concentrating instead on the simpler 2-D case. However, 3-D cues can constrain the deployment of attention. As a function of their distance from fixation, objects project a different image to each eye. For objects at fixation the position of the retinal image in each eye is aligned. Relative to this, objects closer to the observer project an image further to the left in the left-eye and further to the right in the right eye (crossed disparity), the opposite is the case for objects further from fixation (uncrossed disparity). Thus binocular disparity is a strong cue to 3-D distance. It is possible to create binocular disparity from 2-D displays by generating a slightly different image for each eye, and when viewed such displays create a compelling sense of depth for most observers. Nakayama and Silverman (1986; see also Finlayson, Remington, Rettel, & Grove, 2013) used binocular disparity to create search displays where the search items were distributed over two planes one closer to the observer and one further from the observer. In such displays targets defined as a conjunction of depth and colour or motion (e.g. front red target amongst front green targets and red back targets), are found efficiently. This supports the idea that depth can be used to segment the display, leading to parallel search through in one of the two planes. Dent et al., (2012) also recently showed that binocular disparity can be used to guide search during a serial search through heterogeneous letter stimuli. It should be noted though that there are two possible ways to explain the influence of depth on search. Since, in these studies, the elements in one plane were both co-planar and shared binocular disparity, the results could reflect the use of binocular disparity as a feature rather than the grouping of elements into a common plane or surface.

It is certainly true that our experience of the visual world is not limited to fronto-parallel planes, but rather spatially extended surfaces consisting of points at multiple distances from the observer. Nakayama, He, & Shimojo (1995) propose a critical role in vision for these visual surfaces- in particular that extended regions of space behave as groups for purposes of visual computation. Nakayama et al. suggest that surfaces occupy a stage of visual processing subsequent to the computation of features, but prior to object recognition.

Some of the best evidence for a critical role for surfaces comes from a study by He & Nakayama (1995). He and Nakayama (1995) demonstrated that how items group together according to 3-dimensional coplanarity could sometimes be more important than the binocular disparity values of the individual elements involved. They created surfaces of coplanar elements defined by a range of values of stereoscopic disparity, such that two elements from the same surface could have opposite values of disparity. The subjective impression here is of slanted surfaces made up of coplanar elements. Importantly there is no single visual “feature” that consistently distinguishes these surfaces. Binocular disparity varies more within a single surface than between two surfaces, thus a binocular disparity feature alone cannot distinguish the surfaces. Furthermore, although the angle of stereoscopic slant may be conceived of as a feature that could be measured on a single item (e.g. Holliday & Braddick, 1991), in this case stereoscopic slant is the same for both surfaces. Despite the absence of featural differences between the surfaces, He & Nakayama (1995) showed that participants could restrict selection to a particular surface slanted in depth to detect an odd coloured target. Importantly He & Nakayama went on to show that if participants were cued to expect a target at a particular depth from the observer, then they showed a greater cost for occasions when the target did not appear where expected as the distance between the expected and unexpected depth increased. However when these two different depths belonged to the same surface, then the effect of distance was eliminated. One interpretation of this finding is that individuals automatically select whole surfaces even when only part of the surface is relevant.

Thus, slanted surfaces provide a stimulus type where distinct regions of 3-D space may be grouped together, but where there is no single simple *featural* difference that distinguishes the groups. Furthermore, belonging to a particular surface, is not a property that can be assigned to an individual item, in the absence of other items, surface assignment is relative not absolute, and depends simultaneously on multiple items. Thus in the case of slanted surfaces the perceptual differentiation between the surfaces can not be realised by early spatiotopic feature maps as posited by FIT. Importantly for our question there is no basis for feature map inhibition and so if feature map inhibition is necessary for carry-over, carry-over of inhibition on the basis of surfaces should not occur.

Experiments using 2-D stimuli have also documented how both negative inhibitory and positive excitatory attentional biases may be constrained by the surface of a 2-D object. Egly, Driver and Rafal (1994) showed that when one end of an object is cued the cuing benefit also extends to other locations in space that are part of the same object surface. Jordan and Tipper (1999) also similarly showed that inhibition can sometimes spread to other parts of the surface of an object following initial inhibition of a distinct part. Although these studies used 2-D stimuli, they demonstrate the general principle that attentional resources may spread across the surface of an individual object. It remains an open question whether similar constraints operate across multiple items grouped by 3-D cues when segmentation may operate across time, as in preview search.

The current study

The aim of the current study was to assess whether negative carry over effects would emerge in preview search when stereoscopically defined slanted surfaces were used to create groups of items. Though research initially indicated that negative carry-over effects were generated based on colour, there is evidence for effects mediated by other features too. Olivers and Humphreys (2003) and Dent, Braithwaite, He, and Humphreys, (2012) demonstrated effects for orientation, and binocular disparity respectively. Dent et al. (2012) investigated preview search using depth planes defined by binocular disparity. One depth plane was in front of the screen and one was behind. An early appearing set of distractors appeared in one plane, and participants ignored these items. One second later a second set of distractors appeared split over the two depth planes. The target plane was unknown appearing 50% of the time in each plane. When the target appeared in the old previewed plane performance was much slower. The results of Dent et al. (2012) extend the carry-over phenomenon from 2-D colour to stereoscopic 3-D stimuli. However, binocular disparity can be considered a visual feature on par with colour or orientation since there may exist feature maps coding binocular disparity in visual cortex. Thus it remains possible to explain the 3-D disparity case by suggesting inhibition of a particular disparity feature map.

Here we went beyond this by exploring whether the effect generalised to slanted surfaces. Critically there was no single feature that consistently differentiated between items on one surface and items on the other, as the surfaces were created by smooth and continuous variations in stereoscopic disparity defined over the items present. As noted above, two items on the same surface could have opposite disparity features, and two items at nearby 2-D locations but on different surfaces could have similar disparity values. Will negative carry-over effects be observed with such stimuli?

Some authors (e.g. Agter & Donk, 2005; Donk, 2006) have suggested that inhibitory mechanisms in preview search are restricted to the inhibition of "simple" features, with no additional role for direct inhibition of spatial locations. These authors attribute preview benefits found when there are not featural differences between old and new items to onset capture (e.g. Donk & Theuwes, 2001). Any negative carry-over effects from stereoscopic surfaces will not be compatible with a simple feature inhibition plus onset-capture view of preview search, and will require complex spatial structures "surfaces" to be legitimate targets for attentional suppression.

Experiment 1

Experiment 1 was modelled after the experiments reported in Braithwaite & Humphreys (2003). In the critical preview conditions half of the items appeared first in a common surface. After a period of 1 second had elapsed the other half of the distractors appeared on the screen divided up over two different surfaces. Half of the new distractors appeared in the old surface and the other half of the distractors a different new surface. Crucially, the target appeared unpredictably either in the old or in the new surface equally often. Performance in the preview condition was compared against a full set baseline condition in which all the items appeared simultaneously, and a half set baseline condition in which only the second group of items was presented. If previewed surfaces are suppressed, there should be a cost to performance when a new target appears on an old surface, but no cost when it appears on a new surface.

Method

Participants.

Fifteen students, aged between 19 and 21 (M=19.9) from the University of Birmingham took part in return for a payment of £5. Two participants were male and all were right handed. One participant who failed the depth pre-screen was excluded.

Equipment.

The experiment was controlled by software written with MatLab and the Psychophysics Toolbox (Brainard, 1997), running on a MacPro computer. The stimuli were displayed on a Mitsubishi DiamondPro 2070sb monitor running at 120hz. CrystalEyes 4 shutter glasses were used to enable the presentation of a different image to each eye. Responses were collected using a standard USB keyboard.

Stimuli.

The search displays were made up of random collections of distractor letters selected from the set (H, I, V, X) and a single target (Z or N). OpenGL functions were used to simulate two surfaces slanted at an angle of 45 degrees, and separated by 2.2 cm, one surface above the other. Each surface was bounded by an outline square frame (15 x 22 cm), to contextualise the display. The positions of the letters within each surface were constrained by a 9 x 5 grid of 44 possible locations, the centre location being reserved for a fixation cross. Locations were separated by 3.8 cm vertically and 1.4 cm horizontally.

Following transformation each surface was projected as two trapezia each now 15.5 cm long due to foreshortening (see Figure 1). Each surface was characterised by a gradient of binocular disparity from crossed to uncrossed, such that letters at the bottom of one surface appeared in front of the screen and those at the top of the surface appeared behind the screen (in the range ±0.3 degrees of angle of disparity). Importantly two letters at similar 2D locations but on different surfaces would have similar disparity, and two letters at different 2-D locations on the same surface could have opposite disparity. A pre-test ensured that all participants could readily perceive the surface organisation. Displays were rendered with perspective cues, thus the letters themselves were distorted according to perspective, and a gradient of size applied to the surfaces such that items closer to the observer were rendered larger than those more distant (see Figure 1). Letters were simulated with a size of 0.5 cm, after transformation size ranged between 0.4 and 0.6 cm.

Design and procedure.

All participants first completed a pre-screen task before taking part in the main experiment. Participants were presented with the two surfaces, each populated with a set of letters (12 or 24), including a single target (Z or N) that could appear unpredictably in either the top or bottom surface. Participants indicated whether the target was in the top or bottom by pressing either t (top) or b (bottom) on the keyboard. Feedback was given immediately to the participant in the form of the text "correct" or "incorrect" presented in green or red in the centre of the screen. Participants were first familiarised with the displays by completing a practice block of 16 trials. They then went on to complete a total of 40 trials 5 trials of each combination of target location (top or bottom), display size (12 or 24 items), and target location (top or bottom). Participants had to perform without error to progress to the main experiment, but were permitted up to two attempts.

The main experiment consisted of three primary condition types (see Figure 2 for illustration): preview, full-set and half-set. In the preview condition half of the search items appeared all on the same surface for a period of 1 second. A second set of letters was then added to the display, divided over the two possible surfaces top and bottom, 25% of the items in the same surface as the preview and 25% of the items in the other possible surface. The critical variable was whether the target item appeared in the old (50% of trials) or the new (50% of trials) surface.

The full set and half set conditions were created with reference to the preview. In the full set condition the final combined display from the preview condition was presented without any preview, 25% of the items in one plane and 75% of the items in the other plane. The half set condition presented only the new items from the preview, distributed 50 % in each plane. For the preview and the full set conditions two versions were created, one version with a top majority and one with a bottom majority. Each of these five conditions was presented in a separate block. Within each block display size (12 or 24 items), target plane (top or bottom) and target identity (Z or N) was also varied. Participants first completed a set of 5, 16 trial practice blocks, one per condition. In the main experiment participants were presented with each of the five conditions in a separate block twice in succession. Within each half of the experiment the conditions were presented in the same order. The order of presentation of the conditions was counterbalanced over participants. Each block began with a short run of 8 practice trials, followed by a main experimental block of 56 trials.

The trial sequence was as follows: a blank screen appeared for 200 ms, the outline trapezia and fixation then appeared for 1 second in all conditions. In the preview condition the trapezia and fixation were accompanied by the preview distractors. Following this the final search display appeared until participants responded. Participants searched for a Z or N target and pressed “Z” on the keyboard if Z was present and “N” if N was present.

Results

Incorrect responses (3.55%) and RTs >10 or < 0.2s (0.12%) were excluded. See Table 1 for accuracy data, and Figure 3 for mean RT.

Preview vs. full set.

The preview and full set conditions were compared using a four factor 2 x 2 x 2 x 2 within subjects ANOVA on RT with the factors of majority surface (top, bottom), condition (preview, full set), target surface (majority, minority) and display size (12, 24 items). Importantly, although there was a main effect of majority surface $F(1,14)=7.25$, $p<0.05$, and an interaction between majority surface and display size $F(1,14)= 4.88$, $p<0.05$ (performance was faster and more efficient[1] with a top majority), majority surface did not interact with condition or target surface (thus all subsequent analyses collapsed over majority plane). Critically, the three way interaction between condition, target surface, and display size was significant $F(1,14)=4.76$, $p<0.05$. The same analysis carried out on accuracy revealed no significant effects or interactions, all ps>0.05. The three way interaction in RT is consistent with large costs on search efficiency when the target appeared in the majority surface but only in the preview and not in the full set condition (see Figure 3 for graphical illustration).

Separate analyses by target surface confirmed this interpretation. When the target was in the minority surface performance was both faster ($F(1,14)=62.01$, $p<0.0001$ for the condition main effect) and more efficient ($F(1,14)=4.94$, $p<0.05$, for the condition x display size interaction) in the preview compared to the full set condition (search slopes of 39 vs. 53 ms/item in the preview and full set conditions respectively). In contrast when the target appeared in a majority surface the preview benefit (in terms of efficiency) was abolished, despite faster overall performance, ($F(1,14)=13.65$, $p<0.005$, for the condition main effect), performance was equally inefficient in both

[1] Here we use efficiency to refer to the rate of processing the search stimuli as measured by the slope of the function relating RT to display size (ms/item).

conditions ($F(1,14)=1.76$ $p=0.21$, for the condition x display size interaction, search slopes of 75 and 66 ms per item in the preview and the full set conditions respectively). In the full set condition although performance was overall faster when the target appeared in the minority surface, $F(1,14)=5.94$, $p< 0.05$, efficiency did not vary as a function of target surface $F(1,14)=2.31$, $p= 0.15$, indicating that the presence of a majority of items in one surface did not affect efficiency when there was no preview.

Preview vs. half set.

Since how the majority and minority was assigned to a specific surface was shown not to interact with target plane in the above analysis here we collapsed over this variable. Additionally two factor ANOVA with the factors of target surface (top or bottom) and display size (6 vs. 12 items) revealed that there was no significant effect of target surface in the half set condition for either RT ($F(1, 14)= 1.92$, $p=0.19$) or accuracy ($F(1, 14)= 1.14$, $p=0.31$), and so data from the half set condition were collapsed over target surface.

Separate two factor ANOVAs with the factors of condition (preview vs. half set), and display size (12 vs. 24 items for the preview and 6 vs. 12 items in the half set) then compared RTs in the preview condition against RTs in the half set condition (one analysis for the preview when the target appeared in the majority surface, and one for when the target in the preview appeared in the minority surface). When the target appeared in the minority surface in the preview although performance was overall slightly slower in the preview than in the half set condition, ($F(1,14)=8.03$, $p<0.05$, for the condition main effect), the effect of display size was similar ($F(1,14)=1.09$, $p=0.314$, for the condition x display size interaction). Thus in the preview condition participants performed as if there were half as many items present (search slopes of 35 vs. 78 ms/item in the preview and half set conditions respectively), indicating the presence of a preview benefit on efficiency. In contrast when the target appeared in the majority surface performance was both overall slower, ($F(1,14) = 113.32$, $p<0.0001$, for the condition main effect), and more affected by display size, ($F(1,14) = 53.89$, $p<0.0001$ for the condition x display size interaction). Thus participants performed about equally inefficiently in both conditions (search slopes of 75 vs. 70 ms/item in the preview and half set conditions respectively) in the preview case, indicating a disrupted preview benefit.

Two factor ANOVA on accuracy with the factors of condition (preview vs. half set) and display size (12 vs. 24) items, revealed a significant interaction between condition and display size $F(1,14) = 6.66$, $p<0.05$. There were significantly more errors in the preview than in the half set condition but only with 24 items $F(1,14) = 5.57$, $p<0.05$. There was no evidence for any carry-over effect in any of the analyses of accuracy.

Discussion

The results from Experiment 1 were clear. In the full set condition whether the target appeared as part of a majority or minority group made no difference for search efficiency. As a consequence, any unequal distribution of items across depth is not critically impacting on search. In contrast when participants were provided with a preview of some of the items from the majority surface, targets that appeared as part of that majority were much more difficult to find than targets that appeared as part of the minority surface (a cost in excess of 500ms with a display size of 24). Following previous research on the effects of colour in preview search, one explanation of the current data is that when items in the previewed surface are actively ignored inhibition cannot be applied direct to independent locations, but other aspects of the stimuli are also inhibited. In the present case we suggest that the particular surface that items appear on can also be inhibited en-masse (see Braithwaite & Humphreys, 2003; Braithwaite et al., 2003).

If this explanation is true then there follow important implications for understanding attention and search. In particular, since the surfaces cannot be differentiated by any singular non-spatial feature, there can be no one feature-map representing one but not the other surface. Therefore it follows that feature-map inhibition as described by Braithwaite et al. (2003) while sufficient for negative carry over to occur it is not a necessary pre-requisite for preview benefits to occur. Thus, higher order representations of surfaces must be targets for inhibition in addition to feature maps. We return to these implications in the General Discussion.

We note that even when the target appeared in the previewed surface and performance was no more efficient than in the full-set baseline, there was nevertheless an overall benefit to performance. Thus a preview continues to confer some advantage to performance even in the face of negative carry-over effects (when targets fall on the previewed surface). This overall advantage most likely stems from participants beginning the search process more rapidly given a preview. The new items that do not appear in the previewed surface are a minority in the context of the whole display (25%), and do not suffer from negative carry over. Thus initial selection and rejection of these items may be rapid conferring an overall advantage to search. Later stages of search following initial rejection of these high priority items will be inefficient driving the carry-over cost to efficiency.

However, there are two features of the design of Experiment 1 that are suboptimal. Firstly, when the target shared a surface with the preview items it also appeared as part of a majority group. Costs for targets appearing as part of a majority of items have been well documented (see Poisson & Wilkinson, 1992; Braithwaite et al., 2007). Although the effects of distractor ratio here were not significant in terms of efficiency, there was an overall effect, and a trend towards an effect for efficiency. As a consequence it is difficult to rule out a counter-explanation that proposes that what we are observing is an exaggerated distractor ratio effect in the preview case. Secondly, in Experiment 1 target surface and surface novelty are confounded. Although both surfaces are outlined by box in all conditions during the preview, the non-previewed surface is only minimally defined at its boundary, the interior of the surface is not defined by the presence of letters. Thus, when the target shares a surface with the preview it also appears as part of an old existing surface, in contrast when the target does not share surface with the preview it appears as part of a newly onsetting surface. Priority of new objects for attention is well documented (e.g. see Cole, Kentridge, & Heywood, 2004), and there is evidence that new properties of old objects (like motion Abrams & Christ, 2006) may capture attention. Thus in Experiment 1 we may at least in part be observing an effect of capture of attention by a *new* surface. Experiment 2 was designed to address these issues.

Experiment 2

The results of Experiment 1 revealed a negative surface based carry-over effect. However in Experiment 1 when the new target appeared in a surface different to the previewed surface, that surface was both a new surface, and a minority surface. Furthermore the final display of Experiment 1 contained an uneven ratio of items in the two surfaces. In order to address these issues with Experiment 1 in Experiment 2 we adopted the design used in Braithwaite et al. (2003).

In the critical preview condition the first set of distractors appeared distributed over 2 surfaces in the ratio 66:33 %, the second set of items appeared with an equal and opposite ratio 33:66 %. As a consequence no *new* surfaces were created by the second set and the final distribution of the items over the surfaces was equal 50:50 %. Again performance in the preview condition was compared to performance in a half set display of only the new items, and a full set display of the final search array.

In the case of colour previous research has demonstrated that an advantage for a target in a new minority in the half set case, can be turned into a disadvantage in the preview condition (see Braithwaite et al., 2007). In this context this disadvantage has been attributed to greater inhibition of the previewed majority also accruing to the majority feature, and subsequently spreading to new items sharing this feature driving the negative carry over effect.

Method

Participants.

Eighteen students aged between 18 and 24 (M=19.9) from the University of Birmingham participated. One participant was male, and two were left handed. One student who failed the depth pre-screen was excluded.

Equipment and stimuli.

As for experiment 1.

Design and procedure.

Participants completed the same pre-screen task as Experiment 1. In the main experiment of Experiment 2 in the preview condition the items in the first display were presented in both surfaces, 66% (4 or 8) of the items in one surface and 33% (2 or 4) of the items in the other surface, the second set of items were distributed oppositely such that in the final display there were 50% of the items in each surface. The half set condition presented only the second group of items with a majority in one surface. The full set condition presented only the final display with items distributed 50% in each surface. Two versions of the preview and half set conditions were created such that in one version the new minority appeared in the top surface and in the other the new minority appeared in the bottom surface. These five conditions were presented to participants as for Experiment 1.

Results

Incorrect responses (3.14%) and RTs >10 or < 0.2s (0.12%) were excluded. Accuracy data can be seen illustrated in Table 2 and mean RT in Figure 4.

Preview vs. full set.

A three-factor ANOVA with the factors of new minority surface (top or bottom), target position (new minority, vs. new majority) and display size (12 or 24 items) on the data from the preview condition revealed no significant effect of new minority surface, nor did minority surface enter into any interactions with target position (Fs<1.7 for both RT and accuracy). Additionally, a two factor ANOVA with the factors of target surface (top or bottom) and display size (12 or 24 items) on the data from the full set condition revealed a null effect of target surface, and no target surface x display size interaction (Fs<1 for both RT and accuracy). Performance was thus assessed without taking into account exactly how the search items were assigned to the top and bottom surfaces, and the analyses only took into account whether the target appeared in a new majority or a new minority. Two separate two factor ANOVAs with the factors of condition (preview vs. full set) and display size (12 vs. 24 items) were used to compare the full set RT data against the preview with the target in a new minority (old majority), and the preview with the target in the new majority (old minority). When the target appeared in the new majority (old minority) surface there was an overall advantage to search ($F(1,17)=57.709$, $p<0.0001$) but the interaction between condition and display size only approached and did not reach significance $F(1,17)=2.047$, $p=0.171$ indicating approximately equal efficiency in both conditions (despite a trend towards more efficient performance in the preview condition 52 vs. 43 ms/item). When the target appeared in the new minority surface again there was a benefit overall $F(1,17)=8.362$, $p<0.01$ but no significant difference in efficiency $F(1,17)=1.618$, $p=0.22$. However, here the trend is towards less efficient performance in the preview case compared to the full set (58 vs. 51 ms/item). Thus the preview effect here is weak in terms of efficiency. A two factor ANOVA with the factors of condition (preview vs. full set) and display size (12 vs. 24) on accuracy failed to show significant effects or interactions all Fs<1.

Preview vs. half set.

A four factor ANOVA with the factors of new minority surface (top or bottom), target surface (new minority, vs. new majority), condition (preview vs. half set) and display size (12 vs. 24 items in the preview and 6 and 12 items in the half set) was used to analyse the RT data. The factor of new minority surface was not significant nor did it interact with any other factors Fs<1.2, p>0.3, indicating that exactly how the items were distributed over the top and bottom surfaces did not make any difference to search. Critically, the three way interaction between target surface, condition and display size was significant $F(1, 17)=16.98$, $p<0.001$, consistent with large decreases in efficiency as a function of target surface confined to the preview condition. The same analysis with respect to accuracy showed only that overall there were significantly more errors in the preview condition than in the half set condition, ($F(1, 17)=5.815$, $p<0.05$, for the condition main effect), but no other effects were significant (all ps>0.1).

Separate RT analyses by target plane showed that both when the target appeared in the new minority and when it appeared in the new majority performance was both (i) overall slower ($F(1,17)= 71.822$, $p<0.0001$, and $F(1,17)=57.213$, $p<0.0001$, for the condition main effects for the new minority and new majority target respectively) and (ii) more affected by display size

($F(1,17)=49.375$, $p<0.0001$, and $F(1,17)=26.575$, $p<0.0001$, for the condition x display size interactions for the new minority and new majority target respectively) in the preview compared to the half set condition. However, the display size effect was larger in the preview condition when the target formed part of a new minority.

Separate RT analyses by condition were used to further explore this interaction. In the half set condition although performance was overall faster ($F(1,17)=13.62$, $p<0.005$, for the target surface main effect) when the target appeared as part of a minority compared to a majority, performance was equally efficient (search slopes of 52 vs 60 ms/item for minority and majority respectively, $F(1,17)=2.503$, $p=0.132$ for the target surface x display size interaction). In contrast in the preview condition performance was both faster ($F(1,17)=15.54$, $p<0.001$, for the target plane main effect), and more efficient when the target appeared in the new majority (search slopes of 58 vs 43 ms/item, $F(1,17)= 13.389$, $p<0.005$ for the target plane x display size interaction).

Discussion

In comparison to Experiment 1 the magnitude of the preview benefit in Experiment 2 was weaker and was manifested in terms of overall RT but not search efficiency. This reduced preview benefit likely reflects that there is inhibition only of the majority subset of the preview, not all the previewed items (see below). The consequences of active inhibition of only the majority subset were also apparent in the finding that there was a reliable negative carry-over effect when stimuli appeared at the old majority depth. Despite the presence of a significant advantage to overall RT when the target was part of a new minority in the half set condition, there was a significant cost to search when a target appeared as part of a new minority was added to an old previewed majority (search slopes of 58 vs 43 ms/item).

Importantly the negative carry over effect persisted in Experiment 2 despite the fact that in the final display of Experiment 2 there was no majority of items in any one surface and no new surfaces were presented. These results favour an account of the data in terms of surface-based suppression rather than either attentional capture by new surfaces or any interaction between the presence of a majority in the final display and the temporal preview. In the General Discussion we consider the broader implications of these results for understanding negative suppressive processes in search.

The surfaces that were used in Experiments 1 and 2 contained both 3-D stereoscopic and 2-D perspective and size cues. In addition in order to avoid occlusion of item locations from one surface to the other, the spacing was such that items from the two surfaces occupied alternating horizontal regions of the display (see Figure 1). Before we can be confident that what we are observing is a truly 3-D surface based effect, we need to rule out any possible contribution from the 2-D properties of the stimuli. In order to achieve this in Experiment 3 we compared performance with stereoscopic 3-D versions of the stimuli as used in Experiment 2 with 2-D versions where instead of each eye receiving a different image, both eyes received the same image (either left or right). Thus across the 3-D and 2-D versions of the stimuli the 2-D properties are held constant and only the 3-D stereoscopic properties vary. If the negative carry over effect is specific to the 3-D stereoscopic stimuli then it may be properly understood as an effect of 3-D surface based organisation.

Experiment 3

Method

Participants

Eighteen students from the University of Essex aged between 18 and 23 (M=19.6) participated in return for course credit. There were 2 male participants and 2 were left handed. Data from 1 participant who failed the depth pre-screen was excluded.

Equipment

As for Experiment 1.

Stimuli

The stimuli were based on those used in Experiment 2. In addition to stereoscopic 3-D stimuli in which a slightly different image is presented to each eye, we also presented 2-D stimuli, where either the left or right eye image of the appropriate binocular pair was selected randomly, and presented to both eyes. In the 2-D stimuli there was no perception of distinct surfaces.

Design and Procedure

Experiment 3 presented a 2-D and a 3-D version of the preview condition from Experiment 2. Since the location of the majority of items in the preview had made no difference we presented displays always with a majority of preview items in the bottom surface. Items were divided up 66:33 in the bottom and top respectively in the preview and the opposite ratio was present in the new items, 33:66. In the 2-D version participants were presented with a 2-D version of the 3-D stimuli in which either the left or right eye image (randomly) of a 3-D surface pair was presented to both eyes. All the 2-D properties of the items, including the 2-D spacing of items in each surface was preserved but there was no 3-D stereoscopic element. Items appeared flat and no separation between the surfaces was apparent. Target location top or bottom and display size was also manipulated.

Following a depth prescreen as for Experiments 1 and 2. Participants were introduced to each of the 2 conditions 3-D and no 3-D (16 trials each). They then completed four blocks of trials, completing each of the two conditions twice in succession, in a counterbalanced order as for Experiments 1 and 2.

Results

Incorrect responses 2.14% and RTs >10 or < 0.2 s (a further 0.84%) were excluded. Accuracy is illustrated in Table 3 and mean RT in Figure 5. A three factor ANOVA with the factors of condition (3D vs. 2D), target surface (top vs. bottom) and display size (12 vs. 24) items was used to analyse the RT data. The three way interaction between all factors was significant $F(1,17)=4.72$, $p<0.05$. The same analysis conducted on accuracy revealed no significant effects or interactions $Fs<2.4$, $ps>0.14$. Separate analyses by condition were used to decompose this interaction in the RT data. Analysis of RT in the 2D condition revealed only an effect of display size $F(1,17)= 150.88$, $p<0.0001$, indicating that search efficiency was equal regardless of target position. Analysis of RT in the 3D condition revealed main effects of surface $F(1, 17)= 27.24$, $p<0.0001$ and display size $F(1, 17)= 232.89$, $p<0.05$ and an interaction between the two $F(1,17)= 5.693$, $p<0.029$, consistent with much larger less efficient performance when the target appeared in the old bottom majority surface.

Discussion

The results of Experiment 3 provide important control data. When the stimuli formed two distinct surfaces separated in 3-D space, one above the other, there was a substantial negative cost when the target appeared in the old majority surface. Critically this negative surface carry-over effect was present only when binocular 3-D cues were present, and not when only 2-D size, perspective and spatial cues were present. The carry-over effect cannot be attributed to any 2-D properties of the stimuli including 2-D spacing of items. The negative carry-over effect that we observe is a consequence of 3-D stereoscopic organisation of the items into surfaces.

General Discussion

Across three experiments we explored how the presence of multiple stereoscopically defined surfaces interact with the inhibitory bias in preview search. The results were clear; if the target appeared on the surface where the majority of the old items had been displayed it was much more difficult to find than if it appeared on the surface where a minority of the items had appeared. Importantly, these results cannot be accounted for by attentional capture by new surfaces, nor can they be explained by some interaction between distractor ratio effects and preview.

Instead, the results are consistent with the view that as a consequence of being previewed, flexible inhibitory processes act to filter and suppress the representations of the old / irrelevant items. Consistent with a flexible inhibitory weighting account, the nature of these processes means that the other properties of these items tend to be automatically suppressed along with the location. In this particular case, as a consequence of inhibition applied to the locations of the previewed items, inhibition spreads to other unoccupied parts of the previewed surface.

Previous research by Braithwaite and colleagues had shown that negative carry over effects could occur on the basis of colour. The interpretation favoured by these authors was one in which specialised colour feature maps were the mechanism by which attentional suppression was distributed to other items with the majority colour. Results showing that carry-over effects could be preserved even when the old items changed colour when the new items arrived, favoured the importance of feature maps rather than colour based groups.

Dent et al. (2012) showed that negative carry-over effects could occur with 3-D stimuli. New targets appearing in an old depth plane were very difficult to detect. However, since these depth planes were defined by binocular disparity, with all the elements in one plane sharing a single value for disparity, it is possible to explain these findings by suggesting suppression of a disparity feature map. Here we used stereoscopically defined surfaces in order to engineer a situation in which distinct groups of items were present but the difference could not be captured by any particular feature map (including a disparity feature map). The items in these stereoscopic surfaces possess a gradient of values of both size and binocular disparity such that many possible values of these “features” are present in a single surface, and items in different parts of one surface can be more featurally dissimilar than two items nearby on different surfaces. Thus if feature maps are *the* critical mechanism for distributing distractor suppression in preview search (see Agter & Donk, 2005) then this ought to be difficult in the case of surfaces. However, the results presented here show that surfaces are an extremely effective medium for distributing suppressive resources in search. Comparing the current results against the previous results reported by Braithwaite et al. surfaces would seem to behave in a very similar way to colour.

Thus it would seem that current accounts of how inhibitory mechanisms in search operate require revision. At a minimum the targets of attentional suppression in search need to be expanded beyond 2-D locations, and feature-maps, to include 3-D surfaces. One possibility here is to extend the spatial representations posited in models of preview search beyond 2-D locations, to include 3-D surface based representations. It may be that in addition to specific points in space, regions of space may also be inhibited within the same spatial representation system. Osugi, Kumada, and Kawahara, (2009) demonstrated using probe-dot detection that spatial inhibition in preview search may be targeted relatively imprecisely and may spread to regions of space in between grouped elements.

It may be possible to combine the ideas of inhibitory resources spreading across the surface of a single object (e.g. Jordan & Tipper, 1999) with the idea of attention spreading across a coplanar surface defined by multiple objects (He & Nakayama, 1995), to yield inhibition spreading across a surface composed of multiple objects. Although, it seems likely that the status of the inhibition that is applied to unoccupied regions of a surface, and occupied points in space will be different, otherwise it starts to be difficult to explain why probe-dot detection can be more difficult at distractor compared to background locations (e.g. Humphreys et al., 2004). One possibility is that inhibition is maximal at the exact location of an old item, and somewhat weaker at grouped locations (e.g. Osugi, et al. 2009). However, once the feature map loses its monopoly on the distribution of inhibition in search, we can also start to question whether any of these carry over effects in search really stem from constraints imposed by the architecture of the visual system, with a handful of privileged feature dimensions. A whole range of properties of objects may be targets for attentional suppression. Deciding whether the same general mechanisms can account for both feature based and surface based carry over will require further studies. One possibility is that attentional suppression may act at a range of different levels in a visual hierarchy, in which basic features are elaborated into progressively more complex structures, objects, surfaces etc. It will be of interest to determine whether a common mechanism can account for suppression at different levels of such a hierarchy.

One possible alternative to a feature map account of negative carry-over effects is to allow for more flexible and comprehensive representations of objects to be targets for attentional control, something like this is present in the Theory of Visual Attention (Bundesen 1990) and in Attentional

Engagement Theory (Duncan & Humphreys, 1989; 1992). The attentional weight assigned to multiple aspects of old rejected stimuli could be set very low, with the consequence that the selection of new targets with low weight old properties will be delayed. Importantly, the properties of stimuli which are given low weight could be defined very flexibly, perhaps even to include semantic aspects of stimuli. Recently, Osugi, Kumada, & Kawahara (2010) demonstrated that the preview benefit to search could be retained to some degree following graphical changes to old items e.g pictures to Japanese symbols, at least consistent with inhibition of semantic properties. Determining, whether there really are *architectural* constraints on the application of inhibition in search, or if any arbitrary aspect of a stimulus may be inhibited will be an important goal for future research.

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419-433.

		Target in majority		Target in minority	
		12 items	24 items	12 items	24 items
Top majority	Preview	5.24	6.43	3.10	3.81
	Full Set	2.86	2.14	2.86	2.86
Bottom majority	Preview	2.14	4.76	2.38	4.29
	Full Set	3.57	2.86	4.29	3.10
		Top target		Bottom target	
	Half set	3.33	3.10	5.00	2.86

Table 1: Accuracy (percent error) in Experiment 1

Table 2: Accuracy (percent error) in Experiment 2.

		Target in new minority		Target new majority	
		12 items	24 items	12 items	24 items
New minority top	Preview	4.37	3.57	3.17	2.78
	Half Set	3.17	3.37	3.57	2.38
New minority bottom	Preview	2.78	4.17	3.17	4.37
	Half Set	1.59	1.79	2.78	2.78
		Target Top		Target Bottom	
	Full Set	2.58	3.37	3.57	3.57

Table 3: Accuracy (percent error) in Experiment 3.

	12 items	24 items
3-D Target in new minority	2.38	1.59
3-D Target in new majority	2.78	1.80
2-D Target in new minority	2.78	1.79
2-D Target in new majority	2.38	1.59

Figure 1: 2D depiction of the surface stimuli. The two instances of each letter in each position illustrate the left and right eye image of each letter. Letters labelled with 1 correspond to the top surface and letters labelled with 2 correspond to the bottom surface.

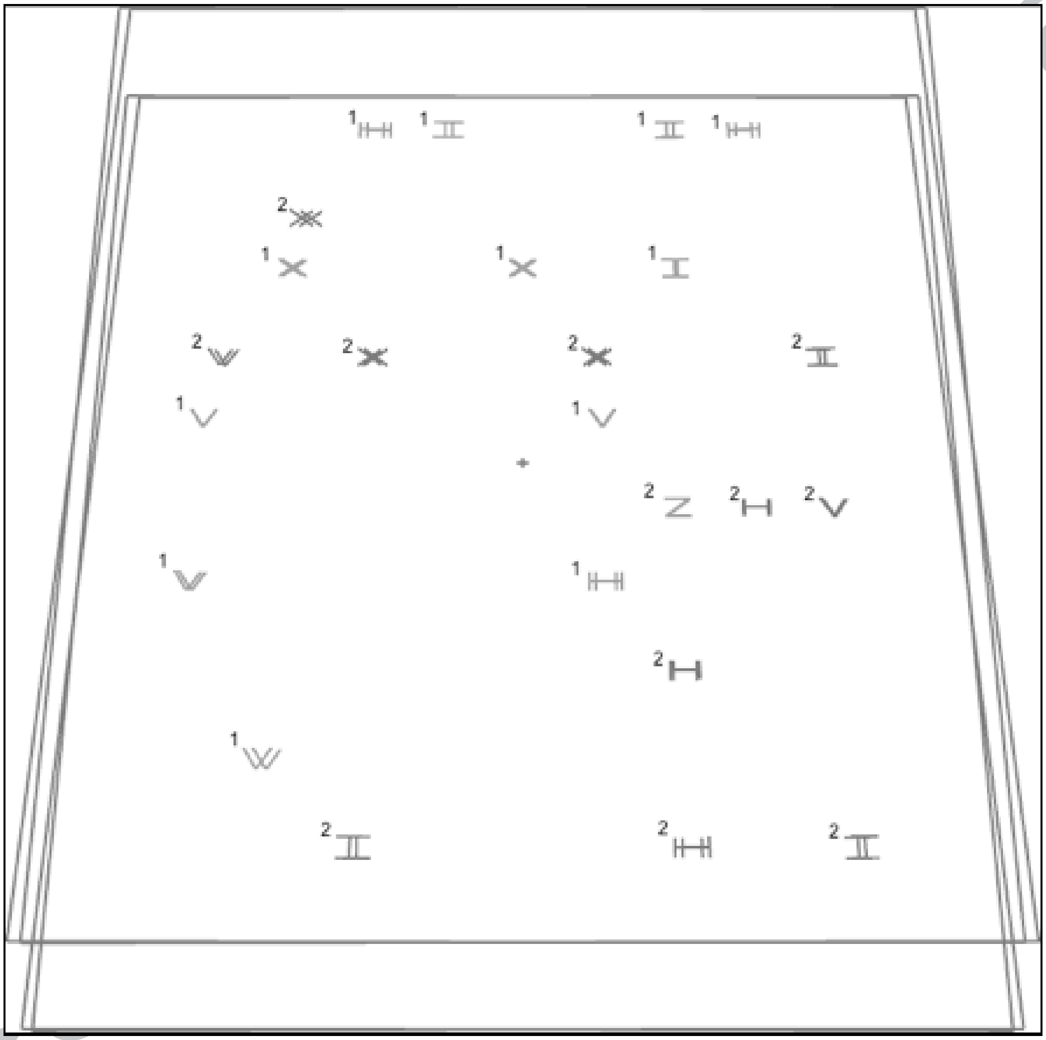


Figure 2: Illustration of the conditions in Experiment 1

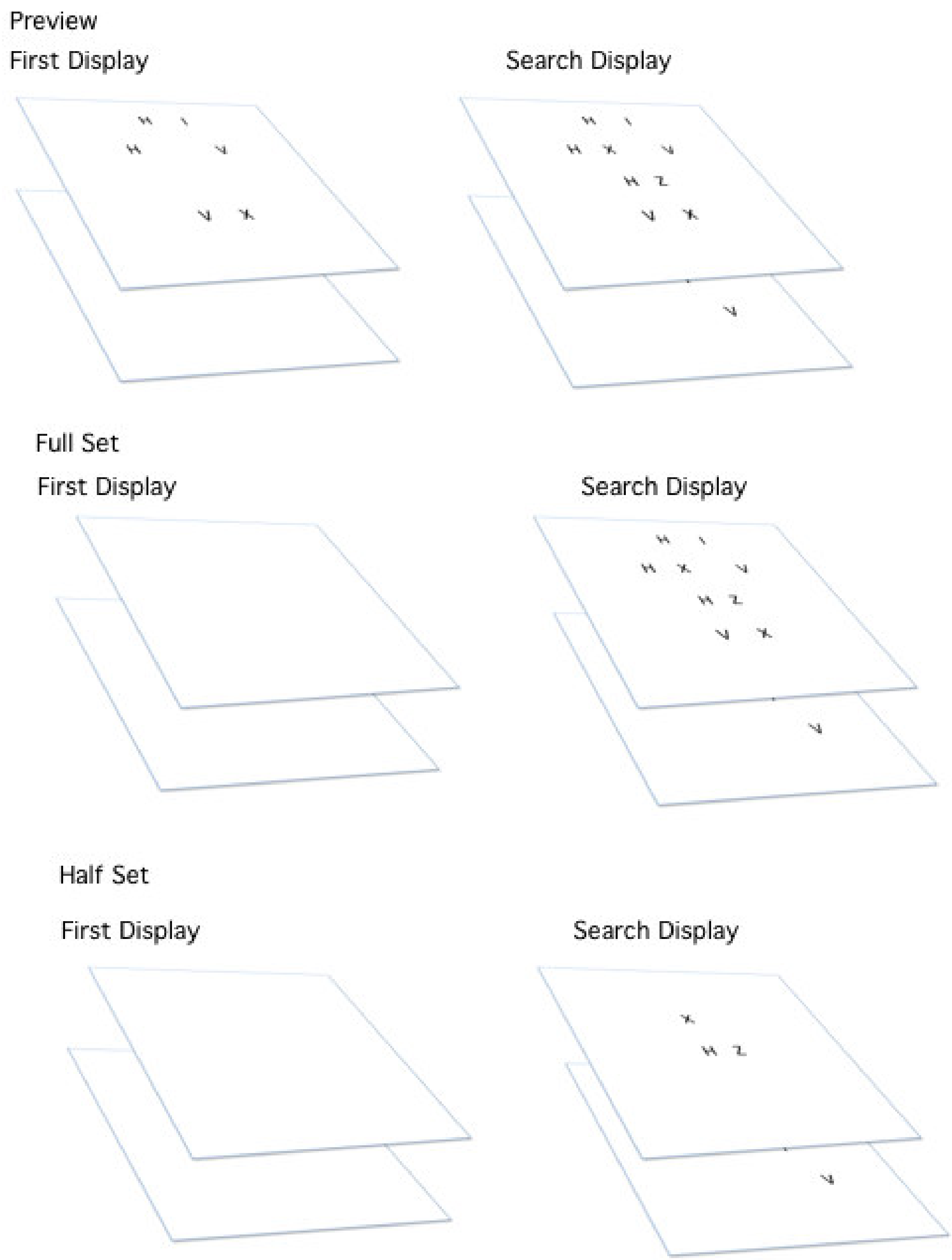
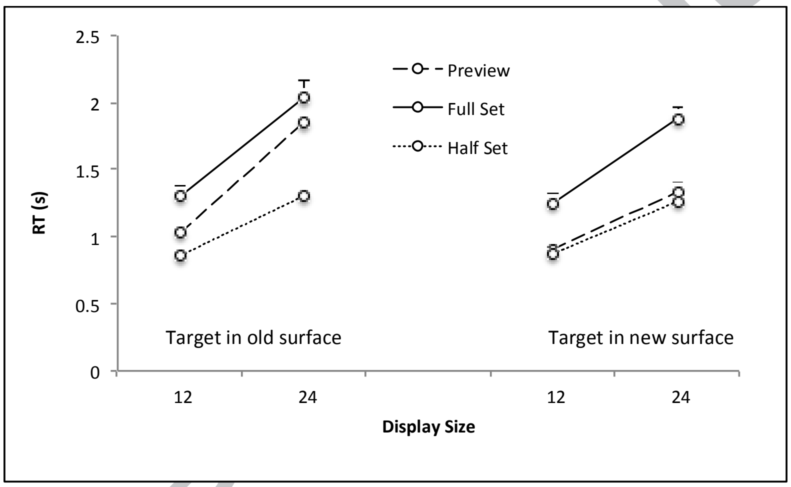


Figure 3: RT in Experiment 1. Upper panel (A) depicts data for a majority in the top surface, and the lower panel (B) depicts data for a majority in the bottom surface. Within each panel the left data correspond to targets in the old surface and the right data to targets in the new surface. Separate lines plot data for each condition as a function of display size in the full set and preview conditions (display size was half this value in the half set condition). Note that the same data is plotted twice for the half set condition (in A and B) for this condition a top target data is plotted on the left and bottom target data on the right.

A: Top majority



B: Bottom majority

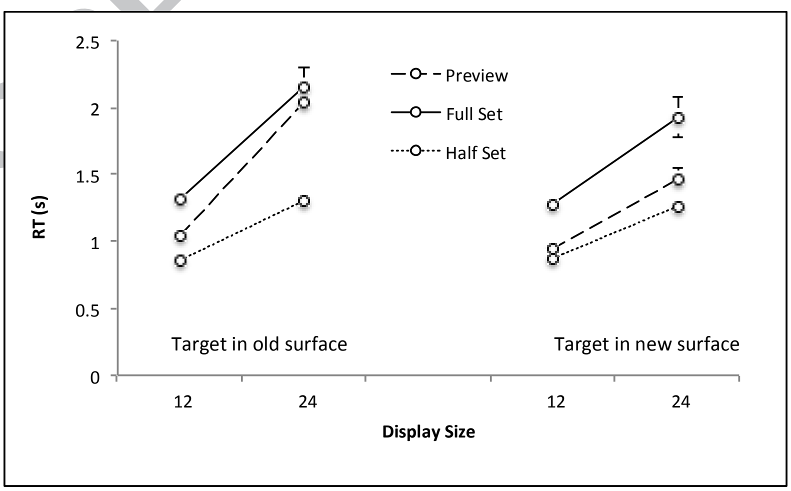
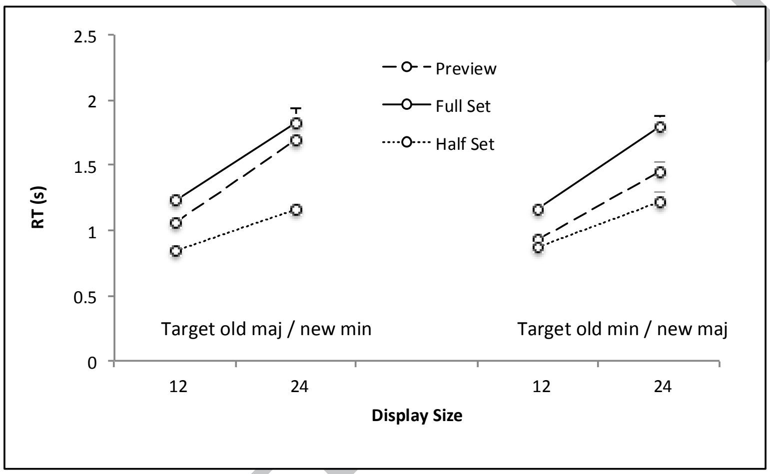


Figure 4: RT in Experiment 2. Upper panel (A) depicts data for a new minority in the top surface, and the lower panel (B) depicts data for a new minority in the bottom surface. Within each panel the left data correspond to targets in the old majority surface and the right data to targets in the old minority surface. Separate lines plot data for each condition as a function of display size in the full set and preview conditions (display size was half this value in the half set condition). Note that the same data is plotted twice for the full set condition (in A and B) for this condition a top target data is plotted on the left and bottom target data on the right.

A: New minority in the top.



B: New minority in the bottom.

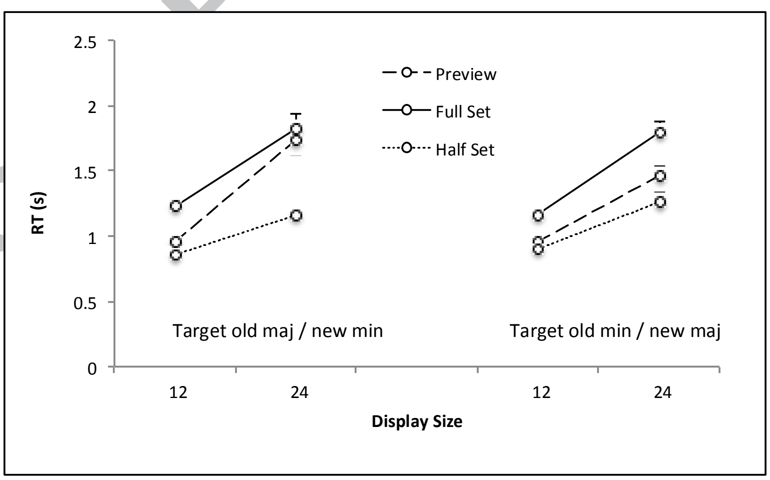
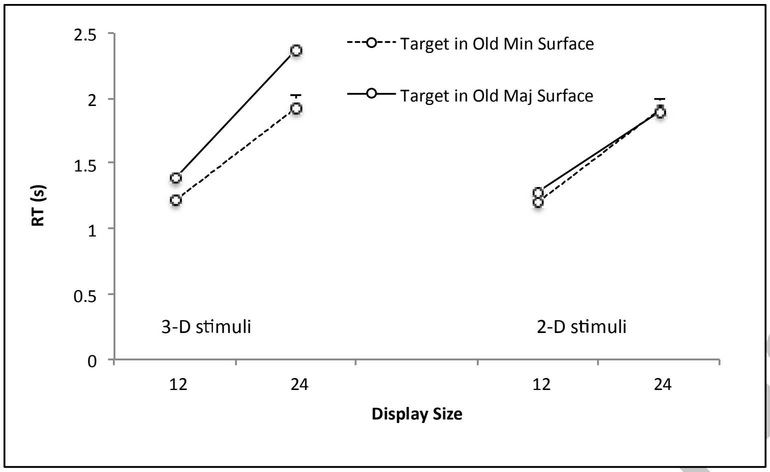


Figure 5: RT in Experiment 3. Data for 3-D stimuli plotted on the left and data for 2-D stimuli plotted on the right. Separate lines plot data for possible target location as a function of display size.



Research Highlights

We investigated how belonging to an ignored slanted surface impacted preview search.

Search efficiency decreased when a new target appeared in an old surface.

When two old surfaces were present, search was more difficult for targets in the surface composed of the majority of items.

Costs for targets appearing in an old majority surface were abolished when stereoscopic 3-D cues were removed.

3-D stereoscopic slanted surfaces constrain the deployment of inhibitory mechanisms in search.