

Search for Multiple Targets of Different Colours: Misguided Eye Movements Reveal a Reduction of Colour Selectivity

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Summary: Searching for two targets simultaneously is often less efficient than conducting two separate searches. Eye movements were tracked to understand this dual-target cost. Findings are discussed in the context of security screening. In both single-target and dual-target search, displays contained one target at most. Stimuli were abstract shapes modelled after guns and other threat items. With these targets and distractors, colour information helped more in guiding search than shape information. When the two targets had different colours, distractors with colours different from either target were fixated more often in dual-target search than in single-target searches. Thus a dual-target cost arose from a reduction in colour selectivity, reflecting limitations in the ability to represent two target features simultaneously and use them to guide search. Because of these limitations, performance in security searches may improve if each image is searched by two screeners, each specializing in a different category of threat item. Copyright © 2011 John Wiley & Sons, Ltd.

INTRODUCTION

In most visual search experiments, there is a single, well-defined target, requiring the searcher to construct an internal representation or template of the target to guide search (e.g. Cave & Wolfe, 1990; Desimone & Duncan, 1995). Many real-world tasks, however, require searching for two or more targets simultaneously. One example, which is the motivation behind the current paper, is common to airport security screeners. Security screeners are faced with the daunting task of scanning multiple x-ray images of luggage for the presence of a number of different threat items, while simultaneously ignoring multiple distractors that may share various properties with the target(s). Previous studies measuring search time and accuracy have shown that searches for multiple targets can be much less effective than conducting separate searches for individual targets (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Menneer, Cave, & Donnelly, 2009). Thus, performance in security searches and other real-world search tasks with multiple targets may be unnecessarily low because of this dual-target cost.

In search for two targets, either (1) a general template is constructed representing both targets, (2) two templates are active simultaneously or (3) control of search is shifted from one template to another over time (Menneer et al., 2007, 2009). Each of these options leads to a different explanation for the dual-target cost. A general template would frequently select non-target objects along with targets, leading to inefficient search. If, instead, each target template narrowly specifies one of the targets, and only one template can guide search at any one time, then some switching from one template to another will be necessary. Such switching

between target representations takes time and resources and is therefore likely to lower performance compared with two separate single-target searches. If two templates can be maintained simultaneously without switching, then there is probably an increased load on resources, and the two simultaneously active templates may compete with one another to guide search towards conflicting feature values, thereby reducing guidance. Understanding dual-target costs and how to avoid them will require an understanding of the target representations that guide search. The current study aims to address this issue by measuring eye movements. Fixations to distractors can indicate the features that are guiding search. This target feature information should help in understanding the target templates guiding search, especially on the question of whether dual-target search is driven by one general template or two separate templates.

Search for multiple targets can be efficient in some circumstances. Search is efficient when the targets are adjacent in stimulus space such that they are linearly separable from the distractors (Barrett, Menneer, Phillips, Cave, & Donnelly, 2003; D'Zmura, 1991; see also Bauer, Jolicouer, & Cowan, 1996). For example, search for red and yellow can be efficient as long as there are no orange distractors. In such cases, target features can be represented by a single feature range without including any distractor values. Dual-target search can also be efficient when targets are feature singletons (Quinlan & Humphreys, 1987; Treisman & Gelade, 1980). In such cases, search is driven by the target features that are very different from the distractor features, resulting in strong stimulus-driven or bottom-up guidance, so that guidance from a target representation is less important. Multitarget search can also be efficient for familiar alphanumeric characters following extensive practice (e.g. Neisser, Novick, & Lazar, 1963; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977), perhaps because the familiarity, similarity and regularity of the alphanumeric stimuli allow for an efficient representation

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of the target set to be constructed and adjusted with experience.

Outside of the specific circumstances described above, multitarget search is generally less efficient than single-target search (e.g. Wing & Allport, 1972), even with alphanumeric characters (Kaplan & Carvellas, 1965). With human observers, dual-target costs in time or accuracy have been revealed in search for colour patches, oriented bars and complex shapes (Menneer *et al.*, 2007) and for x-ray images (Menneer *et al.*, 2009). The dual-target cost has been shown with the same colour-shape conjunctions used in the current study (Menneer, Donnelly, Godwin, & Cave, 2010). In contrast to the research with alphanumeric characters, the dual-target cost has been shown to remain after extensive practice (Menneer *et al.*, 2009, 2010). However, the dual-target cost was reduced when both target categories were similar in colour to one another (Menneer *et al.*, 2009). Such commonality between targets allows features that identify one target to be used in identification of the other. For example, Dykes and Pascal (1981) found that in search for one high-probability (e.g. C) and two low-probability letters (e.g. G and F), performance on the low-probability letter that was similar to the high-probability letter (i.e. G) was higher than that on the dissimilar letter (F). Search will be difficult for security screeners who are required to search simultaneously for targets that come from different categories and differ from one another across multiple feature dimensions. To understand what makes these searches difficult, we need to learn more about how target templates are defined and how they guide search when multiple dimensions are relevant. The eye movement measures in the current study reveal new aspects of the target representations that were not apparent in previous studies. In these new experiments, one dimension (colour) is very informative, while another (shape) is less helpful in guiding search. The specific goal of the current experiments is to use eye-movement measures to compare dual-target search guidance when the two targets share a colour against guidance when the targets have different colours.

Guidance in dual-target search was examined in a controlled manner by using abstract stimuli that share properties with the complex x-ray images that luggage screeners typically examine. Previous research has shown that effects found in real world searches can be recreated using simple stimuli (e.g. rare targets are often missed: Rich, Kunar, Van Wert, Hidalgo-Sotelo, Horowitz, & Wolfe, 2008; Wolfe, Horowitz, & Kenner, 2005). In the current work, we adopted a similar logic by constructing well-controlled, basic stimuli to examine applied search questions. With controlled stimuli, the similarity between target features can be precisely manipulated, leading to more accurate measures of its effect on dual-target cost. By comparing search behaviour across different levels of target similarity, these experiments provide new evidence about the source of the dual-target cost. The results, specifically the eye-movement data, help to determine how the target templates that guide search are represented, and thus facilitate understanding of the cognitive processes underlying dual-target search. They also provide a basis for improving search efficiency in real world search tasks such as those undertaken by airport screeners.

Along with recordings of response time and accuracy, the current investigation included eye movement measurements because they can be informative as to the cognitive processes underlying visual search (Bertera & Rayner, 2000; Rayner & Fisher, 1987; Zelinsky & Sheinberg, 1997; see also Rayner, 1998, 2009; Shen, Reingold, Pomplun, & Williams, 2003, for reviews), including search involving x-ray images (McCarley, Kramer, Wickens, Vidoni, & Boot, 2004). Previous research demonstrates that visual attention and saccadic eye movements are functionally linked, with visual attention preceding and guiding a saccade to a location (Deubel & Schneider, 1996; Greene & Rayner, 2001; Henderson, Pollatsek, & Rayner, 1989), such that it is impossible to effectively direct attention to one location while making a saccade to another location (Hoffman & Subramanian, 1995). However, there is also evidence for a certain amount of independence between covert attention and eye movements (Belopolsky & Theeuwes, 2009; Wu & Remington, 2003). The current study explores the nature of the target representations guiding eye movements, but we suspect that the same target representations also guide covert attention. The frequency with which given features are selected for fixation will indicate the feature set of the target representation. This study is the first one in which such measures have been taken for dual-target search, and therefore provides novel insight into the causes of the dual-target cost.

The stimulus objects in the current experiments varied across 16 different colours, representing a high degree of stimulus heterogeneity, and were designed to prevent bottom-up target pop-out. Fine discrimination was required to distinguish each colour from its neighbors in colour space, but non-adjacent colours were sufficiently different from one another to be easily distinguished, allowing colour to be used effectively to guide search to the targets in this task. The stimuli also differed in shape, but were different configurations of the same two-shape components, and distractors shared shape with the target more frequently than they shared colour, making shape discrimination difficult. Thus, search was likely to be guided mainly by colour rather than shape in these experiments. When the two potential targets share a common colour, search can be limited to items of that single colour. However, when the two targets have different colours, a different selection strategy is necessary, and it is likely to be less efficient.

In both experiments presented here, each participant completed three different searches: (1) A single-target search for one target, (2) a single-target search for a different target and (3) a dual-target search for both targets with at most one of the two targets present on each trial. An efficient search strategy may be possible in Experiment 1, because the two possible targets shared the same colour, which may allow for a single-target template based mainly or entirely on colour. In Experiment 2, though, the two target colours were different and had intervening distractor colours in colour space, which may make it more difficult to guide search with a single template. As described previously, eye movements were measured to reveal the nature of representation in ways that Menneer and colleagues (2007, 2009, 2010) could not. By examining the identity of the objects fixated, we can infer

the template(s) driving search. If a dual-target cost arises in either experiment, the eye movement measures will help to determine the source of the cost, and may also provide insight to the nature of the target representations guiding search.

Most of the x-ray images in security screening have multiple objects overlapping one another, and the difficulty in segmenting objects is one of the factors that limits performance. However, the difficulties that arise from overlapping images are probably best studied separately from the difficulties that arise from multiple-target search. Therefore, in these displays, none of the objects will be overlapping.

In sum, the current investigation has the following goals: (1) To provide a more controlled replication of previous findings with x-ray images that showed a dual-target cost for targets that differ in colour and a reduced cost for targets that share colour; (2) to measure eye-movements to reveal the frequency with which specific features are fixated in order to understand the target representation guiding dual-target search with similar targets and with different targets (3) to apply these results to x-ray security screening training and practice, in which the observer must conduct analogous searches for multiple objects.

EXPERIMENT 1

Method

Participants

Sixteen students from the University of Massachusetts, Amherst with normal colour vision and normal or corrected-to-normal acuity participated in Experiment 1. Participants received 10 dollars for taking part in the experiment.

Apparatus

The stimuli were presented on a 17-inch CRT monitor attached to a computer interfaced with an SR Research Eye-Link II eye tracker operating at 250 Hz calibrated to no more than 0.5° of visual angle error. A chinrest was used to stabilize head movements while both pupil position and corneal reflection were recorded.

Stimuli

Previous experiments with x-ray images of threat items (Menneer et al., 2009) demonstrated dual-target costs in searches for dissimilarly coloured targets (guns and IEDs), but very little dual-target cost in searches for targets that shared colour (guns and knives). The stimuli in the current experiment were abstract shapes that were more carefully controlled, but they were designed to capture the characteristics of these x-ray images with the expectation that they would produce patterns of dual-target interaction similar to those found with the x-ray images. These stimuli ensured the applicability of results to airport security searches. Guns and knives are both constructed from metal, and therefore appear the same colour on x-ray images. These objects were represented here by a flag-shape (gun) and a spatula-shape (knife). Bombs or improvised explosive devices (IEDs) not only include explosives, but also contain metal components,

so they appear as a combination of two colours in x-ray images. They were striped rectangles in the present experiments. Because the specific combination of colour and shape in these stimuli was meant to represent their real world counterparts, the actual stimuli will be referred to as 'guns', 'knives' and 'IEDs' (Figure 1.).

Each stimulus object occupied the same area, being constructed from the same two rectangles ($1.04^\circ \times 0.37^\circ$ and $1.26^\circ \times 2.01^\circ$ visual angle). The gun was an L-shape with the small rectangle extending out from one of the long sides of the larger rectangle. To construct the knife, one end of the small rectangle was placed in the middle of the short side of the large rectangle. The IED was composed of the small rectangle between two halves of the large rectangle to preserve the total area of the shape, with the small rectangle's colour being different from the two halves of the large rectangle, forming a stripe. In addition to these three objects, a plain-rectangle the same size as the IED, but uniform in colour, was used as a possible distractor object (Figure 1).

Stimuli were coloured with the 16 colours used by Menneer et al. (2007, 2010), which were spaced in a ring in CIE_xY space such that a wide range of different hues were represented, and no single colour's relative salience caused it to pop-out from the others (and from which pairs of opposite colours could be selected for Experiment 2).

Each search display contained ten randomly selected items on a white background. Each item occupied one of ten locations equally spaced around a virtual circle with a radius of 9.8° of visual angle around the central fixation point (Figure 1). Each object could appear at a randomly chosen orientation of 0, 90, 180 or 270°. For each participant, a target pair was chosen comprising one gun and one knife of the same colour. The possible distractors included non-target coloured guns, IEDs with the stripe the same colour as the target(s), non-target coloured knives and plain-rectangles. The shape and colour of each distractor was randomly assigned so that each of the four object shapes and each of the 16 object colours had equal chances of appearing as distractors. No shapes other than the plain-rectangle could appear with exactly the same colour as the target, because a gun or knife of this colour would be a target in some conditions, and an IED with this colour for the main body would also have the same colour for the stripe and thus appear as a plain-rectangle.

Procedure

There were three blocked conditions conducted in the following order for each participant: (1) Single-target search for the gun target; (2) single-target search for the knife target; and (3) dual-target search for both targets.¹ Each block had 40 trials, with one target appearing in 50% of the trials. In dual-target search, 25% of the trials contained a single gun target, 25% of the trials contained a single knife target and

¹Presenting the three blocks in the same order for all participants limits one source of variation across participants. It also raises the possibility that differences across the blocks are due to practice or fatigue rather than to the manipulation of the target set. However, the most important comparison in this study will be between Experiments 1 and 2, and because both experiments use the same ordering of blocks, the differences between them cannot be attributed to order.

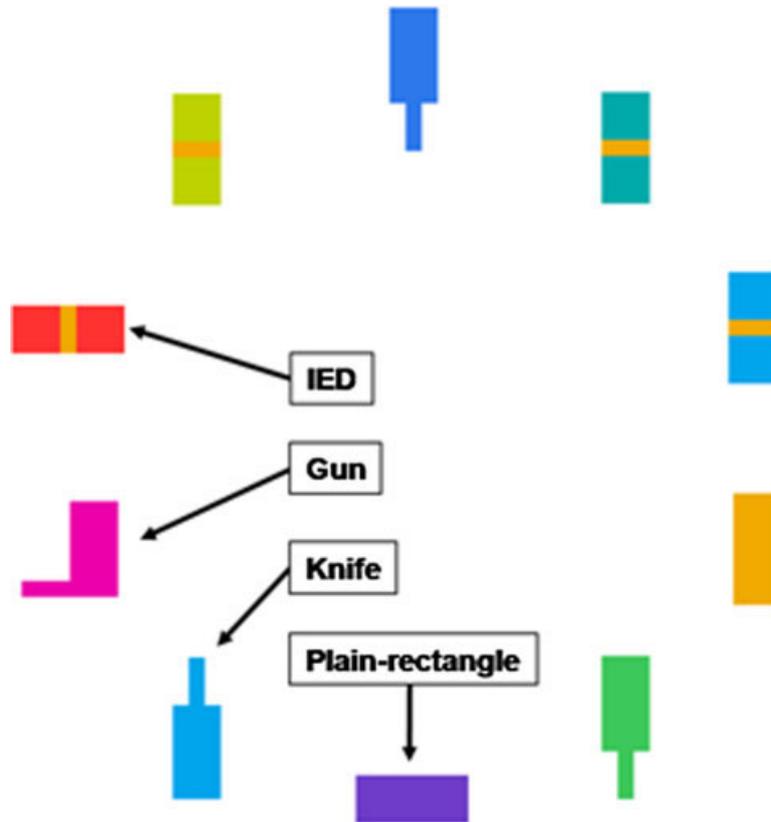


Figure 1. A sample display with each type of object labelled. Note that the names of objects never appeared in the displays viewed by participants. Although this is a sample display from Experiment 1, the same objects types were used for both experiments

50% had neither target present. Participants were informed that the two targets were never both present on the same trial, making the dual-target condition an OR task rather than an AND task (Moore & Osman, 1993). No names were given for the objects, and participants were instructed to search for the targets displayed at the beginning of each trial. The target colours varied across participants so that all 16 possible colours were equally represented across the sample. Each block was preceded by five practice trials.

The sequence of displays for a trial was: (1) A dot at the centre of the screen, which was to be fixated and used to correct for drift in the eye tracker, (2) a reminder picture of the target(s) at the centre of the screen for 1000 ms², (3) a second drift correction dot, the duration of which depended on how quickly a stable fixation was achieved (typically less than one second) and (4) the search array, which was displayed until a response button was pressed. Participants were free to move their eyes once the search array appeared.

Results

Both accuracy and response times (RT) were analysed together in a 3 (Target-Type: gun versus knife versus dual) × 2 (Target-Presence: present versus absent) ANOVA.

²The reminder was required because pilot experiments revealed that participants had trouble remembering the target colour(s) throughout the experiment.

Accuracy

The mean (*SD*) accuracy was 95.1% (0.04%) for gun search, 97.2% (0.04%) for knife search and 96.7% (0.03%) for dual-target search. There was no effect of Target-type, $F(2,90) = 1.508$, $p = .195$, or Target-presence, $F(1,90) = 2.183$, $p = .143$. Thus, there was no evidence of a dual-target cost in accuracy. There was no significant difference in accuracy to gun-present (99.4%, $SD = 0.07%$) versus knife-present (96.3%, $SD = 0.03%$) trials during dual-target search, $t(15) = 1.78$, $p = .096$.

Response times

The mean (*SD*) RT was 1163 ms (516 ms) for gun search, 983 ms (366 ms) for knife search, and 984 ms (342 ms) for dual-target search, which were not reliably different, $F(2,90) = 1.372$, $p = .259$. There was no effect of Target-presence, $F(1,90) = 2.183$, $p = .143$. In the dual-target search, there was no significant difference between RTs to gun-present trials (923 ms, $SD = 458$ ms) and knife-present trials (937 ms, $SD = 402$ ms), $t(153) = .342$, $p = .773$. As with accuracy, there was no evidence of a dual-target cost in overall search time. There is some non-significant evidence of improvement over time in terms of both accuracy and RT, most notably between the first two blocks, but with little difference between the second and the third.

Single versus dual-target searches: Fixated objects

The probabilities of fixating each type and colour of object provided the primary and novel measure for investigating

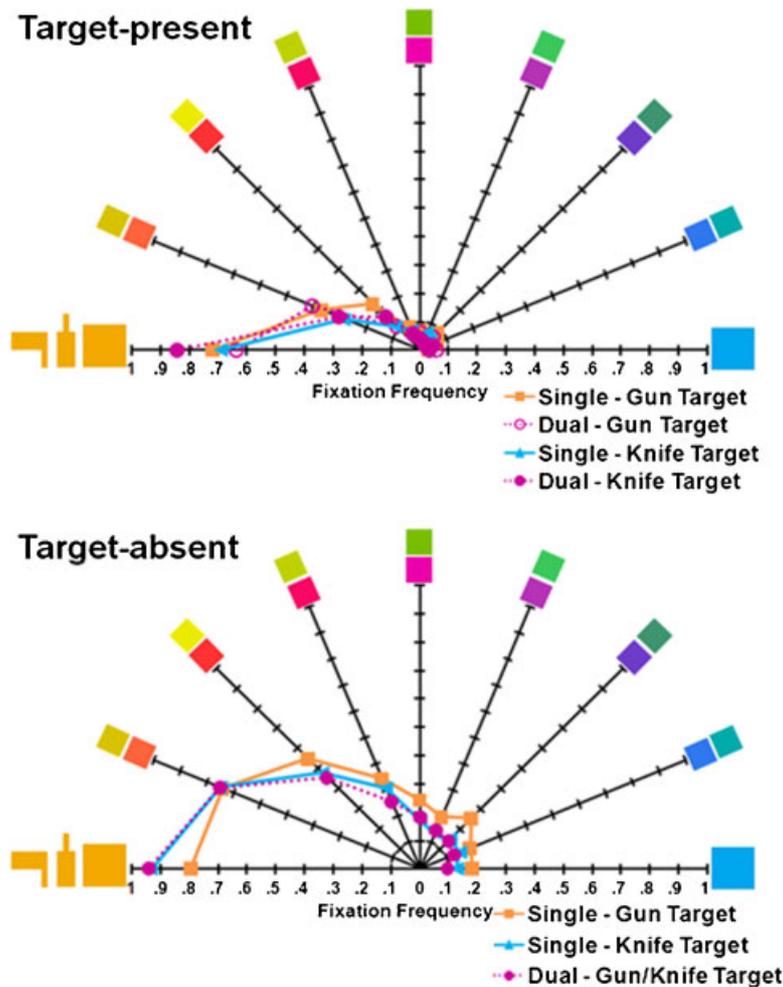


Figure 2. The frequency with which objects of a given colour were fixated once or more during a trial, for single- and dual-target searches on target-present (upper panel) and target-absent (lower panel) trials for Experiment 1. The figures include data for targets and target-colour distractors, although these data were not included in the analyses for reasons provided in the main text. Object colours are represented by the radial lines around the semi-circle. Target colours varied between participants, but for simplicity one possible set of colours, with orange as the target colour, is used to label these lines. The target colour is represented by the line along the bottom left of the graph. Colour distance from the target increases in a clockwise direction from this line, with the line on the bottom right representing the colour on the opposite side of the colour ring, which is the most different from the target colour. Each radial line represents the two colours that are equally distant from the target colour around the colour circle clockwise and counterclockwise, with data averaged across all four shapes

guidance in dual-target search. Analyses compared fixations to objects in single-target searches against those in dual-target search. Each fixation following the initial saccade on each trial was assigned to the closest of the 10 objects (Zelinsky, 1996). The dependent variable was the fixation frequency, defined as the number of instances of each combination of shape and colour that were fixated once or more during a trial as a proportion of the total number of instances of the conjunction that appeared throughout the experiment. Colour was encoded as the distance between the object's colour and the target colour in steps around the ring in CIE xyY colour space.

Figure 2 provides a summary of the fixation frequencies of Experiment 1. Fixations on the target and distractors with the exact target colour are included to allow for a complete picture of the colour guidance driving search. However, some shapes did not appear with exactly the target colour, and fixations to the target may reflect extra confirmation processes as well as colour guidance, and thus the analyses included only distractors with colours different from the

target colour. As will be seen from the analyses described below, there is no evidence of a cost associated with searching for two targets at once compared to conducting individual searches for each target.

To compare performance between single-target and dual-target searches, the fixation frequencies were analysed within a 2 (Target-presence: absent versus present) \times 2 (Search-type: single versus dual) \times 4 (Object-type: gun, knife, IED, plain-rectangle) \times 7 (colour-difference: colour steps away from target colour) analysis of variance. Separate ANOVAs were conducted for gun and knife targets. For the dual-target trials, those with a gun target present were included only in the Gun target ANOVA, those with a knife target present were included only in the Knife target ANOVA and the target-absent trials were included in both ANOVAs.

Gun target

There were more fixations when the target was absent ($p(\text{fix}) = .354$, $SD = 0.025$) than present ($p(\text{fix}) = .137$, $SD = 0.017$), $F(1,15) = 143$, $p < .001$. The number of

Table 1. The summary of the additional eye movement measures for Experiment 1

| Search-target | Average number of fixations | | | Average fixation duration (ms) | | | Average saccade length (°v.a.) | | |
|---------------|-----------------------------|-------|------|--------------------------------|-------|------|--------------------------------|-------|------|
| | Gun | Knife | Dual | Gun | Knife | Dual | Gun | Knife | Dual |
| | 4.7 | 4.0 | 3.9 | 265 | 276 | 285 | 6.2 | 5.8 | 5.9 |

fixations increased with similarity of the colour to the target, $F(6,90) = 93.106$, $p < .001$. There were differences across object types, $F(3,45) = 12.859$, $p < .001$, indicating fewer fixations on the plain-rectangles than on the other shapes. Participants made fewer fixations in dual-target search ($p(\text{fix}) = .194$, $SD = 0.015$) compared with single-target search ($p(\text{fix}) = .246$, $SD = 0.019$), $F(1,15) = 17.515$, $p = .001$, which, being the last condition block, may have benefited from practice.

There was a significant Search-type \times colour-difference interaction, $F(6,90) = 2.33$, $p = .039$, which seemed to reflect unusually high numbers of fixations in single-target search for items two colour steps from the target colour. There were no other significant interactions involving Search-type.

Knife target

As with the gun search, there were more fixations when the target was absent ($p(\text{fix}) = .307$, $SD = 0.019$) than when it was present ($p(\text{fix}) = .096$, $SD = 0.015$), $F(1,15) = 279.834$, $p < .001$. The frequency of fixating an object decreased as colour-difference increased, $F(6,90) = 75.263$, $p < .001$. Shape also guided search, with fewer fixations on plain-rectangles than any other shape, $F(3,45) = 6.933$, $p = .001$. There was no effect of Search-type, $F(1,15) = 2.821$, $p = .114$.

There were no other interactions involving Search-type. As with gun targets, there is no evidence of any cost of searching for two targets over conducting two individual searches.

Single versus dual-target searches: Additional eye movement measures

The average number of fixations, average fixation duration and average saccade length were compared across the three target types (see Table 1). Although participants made significantly more fixations in the single-target gun search than single-target knife search and dual-target search, $F(2,30) = 8.088$, $p = .002$, these differences can be attributed to improvement with practice. The differences in fixation duration were not significant $F(2,30) = 2.705$, $p = .083$.

DISCUSSION

The results are consistent with and expand previous findings by Barrett *et al.* (2003) and D'Zmura (1991) showing that search for multiple targets can be efficient when the target features in the most informative dimension (here colour) are together linearly separable from distractor values. The

Table 2. The fixation probabilities for the targets and the target-coloured distractors for Experiment 1 on target-present trials. '—' denotes instances in which no distractor object of the target colour existed for that search condition

| | Gun | Knife | Rectangle |
|------------------|------|-------|-----------|
| Gun target | 0.95 | — | 0.65 |
| Knife target | — | 0.97 | 0.66 |
| Gun/knife target | 0.93 | 0.99 | 0.77 |

pattern of fixations demonstrates that there was no cost in searching for these two targets that share the same colour.

Clearly colour guides search in this task. In both the single- and dual-target searches, participants could locate objects with colours similar to the target colour quite easily. Participants made relatively few fixations on objects more than three steps on the colour ring from the target colour. Shape was not as informative as colour, but it played some role in guiding search as well, because participants made significantly fewer fixations on the plain-rectangles compared to the other three objects. The plain-rectangles were probably more distinguishable from the other objects because they do not consist of a combination of noticeable small and large constituents as the other objects do.

There was little evidence for a cost from searching for two targets at once versus conducting two independent searches (Figure 2). Because the few interactions between other factors and the single/dual-target factor were of little consequence, we can conclude that adding a second target had little effect on the use of colour or shape during search. Therefore, when target objects share the same colour and are difficult to discriminate along the dimension of shape, there is no detectable cost associated with conducting one search for both targets as opposed to two separate individual searches.

The lack of a dual-target cost suggests that search in this task could be guided by a single template specifying the target colour. If so, this template probably also contained some information about shape or component size that allowed plain-rectangles to be avoided. If the template was purely based on colour, then we could expect the target-coloured distractor to be fixated as often as the target, but as Table 2 shows, this is not the case. These results could also be explained by assuming that separate templates for the two different targets were guiding search simultaneously, and that the colour guidance from the two templates was very effective because there was no interference between them. Whether search was done with one or two target representations, the shared target colour in this task makes it possible to search for two separate targets just as efficiently as searching for each individually.

These results are applicable to search tasks involving screeners. Given the task to search for two targets that differ subtly in shape but share the same colour, search can be guided by the common colour between the two. In terms of scanning luggage for threat items, guidance could be directed by this common colour and saccades should be directed in an efficient manner. As discussed previously, guns and knives are both typically constructed from metal and thus are represented by similar colours in x-ray images. The results of the current experiment extend those of previous research involving actual x-ray objects (Menneer et al., 2009) by revealing that efficient search is accomplished by directing saccades to similar coloured objects in a manner that would be just as efficient as searching for the two separate types of objects individually. The question that remains is whether eye-movement data can also inform understanding of the dual-target cost when the two targets differ along both colour and shape, which is the focus of Experiment 2.

EXPERIMENT 2

Previous research has suggested that dual-target search for very different targets leads to a cost in accuracy (Menneer et al., 2007, 2009, 2010). The goal of Experiment 2 was to use eye-movement data to explore colour and shape guidance in dual-target search for two targets that differ along both features, in order to better understand the source of this cost.

Method

Participants

Sixteen additional students from the University of Massachusetts, Amherst with normal colour vision and normal or corrected-to-normal acuity participated in Experiment 2.

Stimuli

Target pairs included a gun of a given colour and an IED of the colour on the opposite side of the colour ring, but with a stripe of the same colour as the gun target. The IED reflects the multi-component nature of x-ray images of IEDs used in an earlier experiment demonstrating dual-target costs (Menneer et al., 2009). One of the main characteristics of IEDs is the explosive material, but metal components are also present, and appear in a very different colour than the explosive. The IED images used here have a similar combination of colours. It is probably the colour of the main body that is most useful in search, rather than the smaller, and therefore less salient, stripe colour.

Each participant was assigned a different target pair. The selection of the distractor objects was generally the same as in Experiment 1: Distractor shapes and colours were assigned randomly, and the stripe of each IED was the same colour as the gun target. The distractor set was therefore the same across both experiments, except that the knife target in Experiment 1 now appeared as a distractor, and the IED was a target rather than a distractor. In other words, the same objects appeared in Experiment 2 as in Experiment 1, except that distractor and target roles were modified. As a consequence of having differently coloured targets, but maintaining the same stimulus set as Experiment

1, the restrictions on the target-colour distractors that existed in Experiment 1 were reduced in Experiment 2. Knife and plain-rectangle distractors could be the same colour as the gun target. Gun, knife and plain-rectangle distractors could be the same colour as the main body of the IED target.

Procedure

The procedure was the same as in Experiment 1 except that participants searched for the IED target in the second single-target search, and both the gun and IED targets in the dual-target search. To allow for a direct comparison between the two experiments, the order of presentation of the blocks was the same as Experiment 1 (single-target search, single-target search, dual-target search).

Results

The experimental design and analyses were the same as Experiment 1. As in Experiment 1, participants in all conditions of Experiment 2 effectively used colour to guide search by fixating more objects with colours similar to the target.

Accuracy

The mean (*SD*) overall accuracy was 94.8% (0.07%) for the gun search, 95.9% (0.06%) for the IED search and 90.9% (0.07%) for the dual-target search. There was a main effect of Target-type, $F(2,90) = 3.137$, $p = .048$. A contrast revealed that the single-target searches produced reliably lower error rates compared to the dual-target search, $F(1,30) = 7.04$, $p < .05$, providing evidence for a dual-target cost. There was no significant difference between single-target gun and IED searches, $F < 1$. There was no significant effect of Target-presence, $F(1,90) = .033$, $p = .856$. In the dual-target search, participants were significantly more accurate when the IED (96.3%, $SD = 0.04\%$) was the target compared to the gun (85.6%, $SD = 0.07\%$), $t(15) = 2.31$, $p = .036$.

Response times

The mean (*SD*) RT was 1149 ms (339 ms) for the gun search, 970 ms (264 ms) for the IED search and 1579 ms (343 ms) for the dual-target search. There were significant main effects of Target-type, $F(2,90) = 27.08$, $p < .001$, and Target-presence, $F(1,90) = 9.270$, $p < .001$, and a significant interaction between the two, $F(2,90) = 4.761$, $p = .011$. Contrasts showed that performance with two targets was significantly worse than with single targets, $F(1,30) = 47$, $p < .001$, and that responses were significantly faster in the single-target IED searches than in the single-target gun searches, $F(1,30) = 4.2$, $p < .05$. The interaction revealed that in the IED and dual-target search conditions, participants were significantly faster to respond when the target was present than when it was absent ($ps < .05$), with no difference in the gun condition. For the dual-target search, there was no significant difference between RTs on gun-present (1233 ms, $SD = 273$ ms) and IED-present (1325 ms, $SD = 294$ ms) trials, $t(136) = 1.25$, $p = .213$. There was evidence of an RT cost when searching for two targets compared to searching for just one, and the lack of difference between the first and second blocks argues against practice effects.

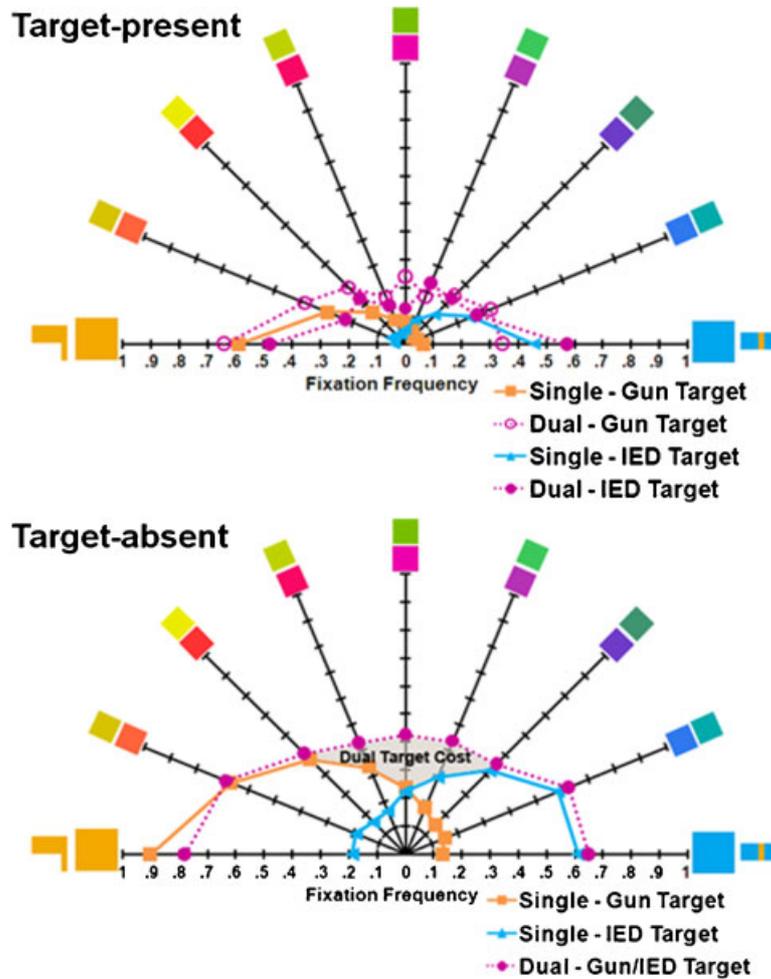


Figure 3. The frequency of fixating a given object colour in single- and dual- target conditions on target-present (upper panel) and target-absent (lower panel) trials for Experiment 2. The object on the left side of the x-axis represents the colour of the gun target while the object on the right side of the x-axis represents the colour of the main body of the IED target. The two colours at the top of the vertical line at the centre of each panel signify the colours least similar to both targets on the colour ring. The shaded area labelled 'dual-target cost' between the single- and dual-target lines represents the increased fixation rate on objects dissimilar to both search targets

Single versus dual-target searches: Fixated objects

To evaluate the dual-target cost in terms of the number of fixations, the same type of analysis was applied to the fixation frequencies as in Experiment 1.

Gun target

The fixation frequency was higher for objects with colour similar to the target, $F(6,90) = 34.009, p < .001$. Objects were more likely to be fixated when the target was absent ($p(\text{fix}) = .316, SD = 0.020$) than when it was present ($p(\text{fix}) = .113, SD = 0.011, F(1,15) = 145.584, p < .001$). Objects were more likely to be fixated in dual-target search ($p(\text{fix}) = .366, SD = 0.014$) than in single-target search ($p(\text{fix}) = .214, SD = 0.014, F(1,15) = 234.505, p < .001$).

During single-target search, the four object types were fixated at approximately the same levels of frequency, but in dual-target search, the IEDs were more likely to be fixated than the other three object types, producing a significant Search-type \times Object-type interaction, $F(3,45) = 25.644, p < .001$. The combination of two colours in the IED may have been relatively easy to detect even when it is not fixated,

and so when this pattern is associated with one of the targets, it apparently draws more fixations.

As would be expected, colour was used very differently between single-target and dual-target searches. When searching only for the gun, objects with a colour similar to the target were more likely to be fixated, as in Experiment 1. In dual-target search, the main-body colour of the IED target was very different from the colour of the gun target, and there were many fixations on colours similar to one target colour or the other, producing high fixation rates at both ends of the scale in Figure 3. This difference between the single-target and dual-target colour selection is amplified when the target is absent, producing a significant interaction between Target-presence, Search-type and colour difference, $F(6,90) = 3.757, p = .002$ (Figure 3).

IED target

As with the gun targets, objects with colours similar to the target received more fixations, $F(6,90) = 33.034, p < .001$, and more objects were fixated when the target was absent ($p(\text{fix}) = .294, SD = 0.027$) than when it was present ($p(\text{fix}) = .097, SD = 0.013, F(1,15) = 336.956, p < .001$). There were more objects fixated in dual-target search

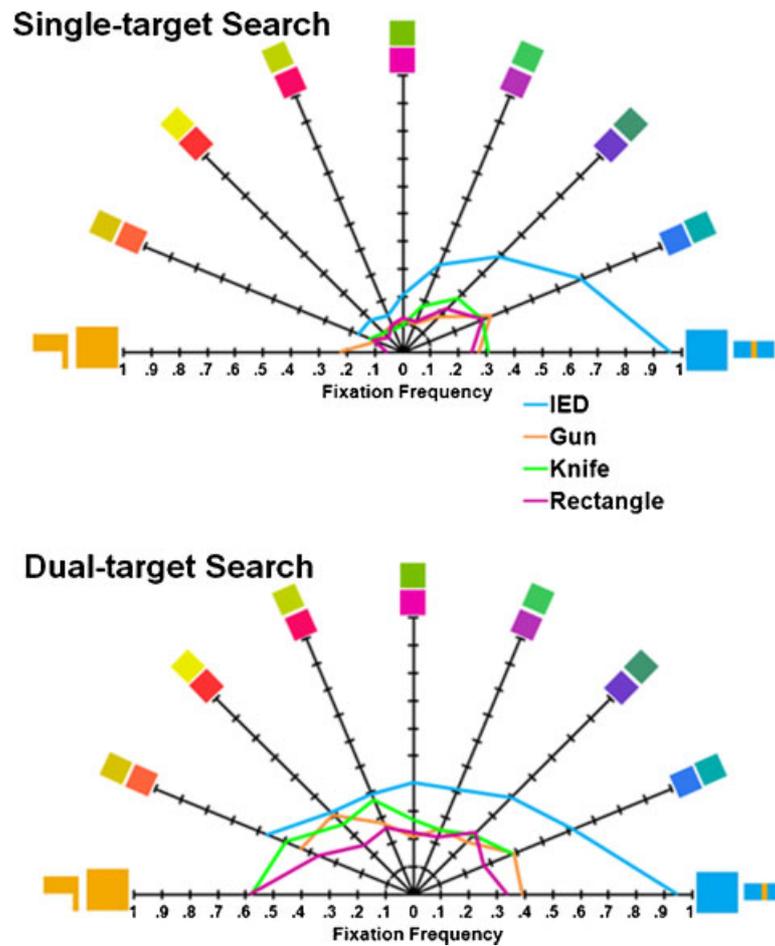


Figure 4. Fixation frequencies for the different object types during the single-target IED search (upper panel) and dual-target search (lower panel) for Experiment 2. As before, the object colours are represented by the radial lines around the semi-circle. The body of the IED target was always the colour furthest from the gun colour on the colour ring. Thus, the gun target colour is represented on the bottom left and the colour of the main body of the IED target is represented on the bottom right

(($p(\text{fix}) = .366$, $SD = 0.040$) than single-target search (($p(\text{fix}) = .195$, $SD = 0.020$), $F(1,15) = 146.481$, $p < .001$). As observed with the gun targets, there were more fixations on the IED than the other objects. Unlike the gun target analysis, this occurred in the single-target search as well as the dual-target search, presumably because both searches involved search for an IED target. Elevated fixation frequencies on the IED objects was mainly evident on target-absent trials, producing a significant Target-presence \times Object-type interaction, $F(3,45) = 11.545$, $p < .001$.

A Search-type \times Object-type \times colour interaction, $F(18,270) = 3.824$, $p < .001$, revealed that in the single-target search, fixations were limited to objects with colours close to the target colour, although for IED objects the range of colours fixated was larger than for other object-types (Figure 4). However, a cost was revealed in dual-target search, with very limited colour selectivity and only a hint of shape selectivity.

Perhaps the most striking results of Experiment 2 are seen when comparing the fixation frequencies across single and dual-target searches. Many more objects were fixated in dual-target search than in single-target searches, especially on target-absent trials. The dual-target cost was evidenced by more fixated objects overall and more fixations on objects

with colours very different from either target colour, as seen in the centre part of Figure 3.

There is an alternative explanation for the high number of fixations in the dual-target condition within this middle range of colours that does not involve a dual-target cost in fixations. Perhaps some shapes are fixated more in the single-target gun search, while other shapes are fixated more in the single-target IED search. However, an examination of the fixations separately for each shape within the middle range of colours rules out this alternative. Within each of the four shape categories, the dual-target search produced more fixations than either single-target search for the colours not similar to either target colour. These greater fixation frequencies demonstrate that fixations are made in dual-target search that do not occur in either single-target search. This pattern of fixations is further reflected in the subsequent analyses.

Single versus dual-target searches: Additional eye movement measures

The same three dependent measures were compared across the three target types as in Experiment 1. In dual-target search, the eyes tended to fixate more locations, spend less time at each location, and travel farther from one location to the next compared with both single-target searches, resulting

Table 3. The summary of the additional eye movement measures for Experiment 2

| Search- target | Average number of fixations | | | Average fixation duration (ms) | | | Average saccade length (°v.a.) | | |
|----------------|-----------------------------|-----|------|--------------------------------|-----|------|--------------------------------|-----|------|
| | Gun | IED | Dual | Gun | IED | Dual | Gun | IED | Dual |
| | 4.4 | 4.0 | 6.4 | 286 | 274 | 250 | 6.2 | 6 | 6.9 |

in significant differences in the average number of fixations, $F(2,30)=93$, $p<.001$, fixation duration, $F(2,30)=20$, $p<.001$, and saccade length, $F(2,30)=19$, $p<.001$ (Table 3).

DISCUSSION

In both single-target searches, participants used colour effectively to guide search, fixating more often on objects with colours similar to the target colour. The gun target search was the same as Experiment 1 and produced similar results. The IED target contained two colours, and the colour combination may have complicated search, or the boundary between two adjacent colours may have created an effective feature for enhancing search guidance. Given the differences between the targets across Experiment 1 and Experiment 2, we need to establish that these differences do not explain the difference in the dual-target cost between the two experiments. Participants located the IED target with the same accuracy as the gun target in single-target searches, and the IED searches were actually a bit faster. The colour fixation frequencies indicate that search was effectively guided to items that shared colour with the main body of the IED target. It could be that the IED is actually a more difficult target than the gun, and the equality in performance is only achieved through practice between the gun search (first block) and the IED search (second block). However, this benefit from practice would also contribute to the dual-target search (final block), so initial differences in difficulty between the gun and IED would not explain the dual-target cost. In addition, in dual-target search, accuracy for the IED target is actually higher than it is for the gun target, suggesting that, if anything, dual-target search should benefit from including the IED compared to a single-colour target. Furthermore, the finding that more IED objects were fixated when searching for an IED target indicates that the two-colour combination is more salient amongst single-colour objects than the other objects are. This finding suggests that those searching for IEDs in real x-ray images would fixate objects that have a combination of the two component colours of IEDs; one representing the organic material (explosives) and the other representing the metal wires. Although IED search may be conducted differently because of the combination of target colours, the single-target searches with these abstract stimuli show no evidence for differences in effectiveness of guidance or task difficulty between the gun target and the IED target.

In the dual-target condition, colour still guided search, but less effectively than in the single-target searches. The reduction in colour selectivity can best be seen in the distractor colours that were equally dissimilar from both of

the target colours, which received significantly more fixations compared to the single-target conditions. The dual-target cost in this experiment might be attributed to complications that arise from having a target defined by two colours. However, another recent study (Stroud, Menneer, Cave, & Donnelly, 2011) has demonstrated a dual-target cost with two targets that are each defined by a single colour, suggesting that the dual-target cost here is not caused by a two-colour target.

In both types of search in this experiment, there is some evidence that guidance is not based entirely on target colours, because there are significantly more fixations on the distractor-IEDs compared to the other three object types. In addition, if only colour were being used, the probabilities for fixating targets would be the same as for target-colour distractors, which is not the case (Table 4).

General Discussion

The current study investigated the cognitive processes driving multitarget search in order to identify ways of improving performance in applied search tasks. The stimuli used in these two experiments isolated properties of real world objects with the goal of determining how these properties produce the benefits and costs in search for multiple objects. The first aim was to investigate the data patterns from previous studies involving x-ray images, but to have more control over the manipulations of colour and shape. Results were in agreement with these previous studies. Experiment 1 demonstrated that search for two targets that shared the same colour, but differed slightly in shape, was just as efficient for searching for each individually. The second experiment revealed that search efficiency was greatly reduced when the two targets differed maximally in colour and were comprised of very different shapes. Extending previous work, the eye movement data collected here reveal a likely source of this dual-target cost. By plotting the fixation patterns, we were able to assess how colour and shape guided search. Specifically, the longer reaction times and lower accuracy in dual-target search can

Table 4. The fixation probabilities for the targets and the target-coloured distractors for Experiment 2 on target-present trials. The bottom two rows represent the two possible target colours from the dual-target condition

| | Object shape | | | |
|-------------------------------|--------------|-------|------|-----------|
| | Gun | Knife | Bomb | Rectangle |
| Gun target | 0.96 | 0.69 | — | 0.64 |
| IED target | 0.43 | 0.49 | 0.96 | 0.42 |
| Dual search gun target colour | 0.87 | 0.64 | — | 0.45 |
| Dual search IED target colour | 0.42 | 0.49 | 0.94 | 0.38 |

be attributed to misguided saccades directed towards objects with nontarget colours.

The second motivation was to learn more about how participants mentally represent two targets during search as revealed by their patterns of eye fixations. Based on the high degree of colour selectivity exhibited in Experiment 1, participants apparently either maintain two separate templates or are able to create a single template that contains the features common to both targets. Turning to Experiment 2, Menneer et al. (2010) utilized the same stimuli and demonstrated a dual-target cost based on response time and accuracy measures. Experiment 2 shows that this cost arises because of a reduction in colour selectivity. During simultaneous search for two targets of different colours, fixations are distributed more widely than in single-target search, and include more fixations to objects that are not similar to either target colour. Participants cannot limit their eyes to either of two different target colours as effectively while excluding other colours. If the dual-target search were broken down into two single-target searches, the colour selectivity would be restored and less time would be wasted fixating items that are clearly not targets.

While Experiment 2 demonstrates the nature of the interference in dual-target search, Experiment 1 demonstrates why, for some combinations of targets, there is no dual-target cost. In Experiment 1, both targets had the same colour, and thus the colour information could be used effectively to guide eye movements towards either of the two targets. The shape differences between targets and distractors were so subtle that they were of only limited use in guiding search.

These results provide constraints for theories of visual attention. Even though selection mechanisms can effectively exclude distractors based on colour and other features, that selection is limited by the target representation(s) driving search. This representation cannot include two different colours simultaneously in a way that leads to effective selection of these two colours. There are multiple plausible accounts for this limitation on dual-colour search. Perhaps search can only be guided by a single template, or more resources are required to maintain two target templates or to switch between them over time. Experiment 1 demonstrates that dual-target search is efficient if both targets share a colour, so there must be some flexibility in this situation. If search is guided by a single template, then that template can apparently specify a single colour shared by two targets, but cannot specify two different target colours. Alternatively, the two colours may be represented within a single template in such a general way that some distractor colours are also selected. These accounts are generally consistent with the difficulty in searching for one object with two colour regions (Wolfe, Yu, Stewart, Shorter, Friedman-Hill, & Cave, 1990). Interestingly, though, a later study by Wolfe, Friedman-Hill, and Bilsky (1994) suggests that two-colour templates can guide search when they represent a complex structured object with parts. A final possibility is that two templates can be easily maintained simultaneously as separate representations, but when they specify two different target colours, the resulting interference caused by these two control-signals pulling in different directions leads to more selection of

locations with neither target colour. This account is more difficult to reconcile with the Wolfe et al. findings. A greater understanding of the theoretical underpinnings behind dual-target search will further contribute to the practical applications involving similar processes.

The final goal of this study was to connect these findings to real world searches among objects containing analogous combinations of features, as in airport security screening. The patterns of eye-movements from these two experiments can be used to explain the response time and accuracy results from Menneer et al. (2009) that showed a much reduced dual-target cost for similarly coloured guns and knives, and a persistent large cost for differently coloured guns/knives and IEDs. Overall, the current experiments elucidate the importance of colour in visual search for multiple targets as long as the target colour can be readily discriminated from the distractor colours. When search involved two objects of the same colour, saccades were directed in an efficient manner towards target-coloured objects. However, this colour guidance was greatly reduced in search for differently coloured targets. The cost with x-ray images is therefore likely to arise from fixations to objects that are dissimilar in colour to either target.

While further experimentation with x-ray images (e.g. Menneer et al., 2008a) is required to reach firm conclusions, it is possible to make recommendations for changes to make airport security screening training and procedures more effective and reduce errors. One suggestion would be to modify the behaviour of airport screeners through training. Such training could promote awareness of the misguidance to irrelevant distractors as a source of error. The aim would be to reduce the behaviour and eliminate the errors, by perhaps learning to search for one target independently of the other. An alternative to such error training, although perhaps with more financial cost, is to split the search task across screeners, with each screener specializing in search for threat items that share colour. For example, one screener would search only for metal-threats (blue) and another would search only for explosives (orange) (Menneer et al., 2009). The eye-movement data from the current experiment justifies this recommendation by directly demonstrating that the dual-target cost is accompanied by a reduction in guidance.

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