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Search for Two Categories of Target Produces Fewer Fixations to Target-Color Items

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Searching simultaneously for metal threats (guns and knives) and improvised explosive devices (IEDs) in X-ray images is less effective than 2 independent single-target searches, 1 for metal threats and 1 for IEDs. The goals of this study were to (a) replicate this dual-target cost for categorical targets and to determine whether the cost remains when X-ray images overlap, (b) determine the role of attentional guidance in this dual-target cost by measuring eye movements, and (c) determine the effect of practice on guidance. Untrained participants conducted 5,376 trials of visual search of X-ray images, each specializing in single-target search for metal threats, single-target search for IEDs, or dual-target search for both. In dual-target search, only 1 target (metal threat or IED) at most appeared on any 1 trial. Eye movements, response time, and accuracy were compared across single-target and dual-target searches. Results showed a dual-target cost in response time, accuracy, and guidance, with fewer fixations to target-color objects and disproportionately more to non–target-color objects, compared with single-target search. Such reduction in guidance explains why targets are missed in dual-target search, which was particularly noticeable when objects overlapped. After extensive practice, accuracy, response time, and guidance remained better in single-target search than in dual-target search. The results indicate that, when 2 different target representations are required for search, both representations cannot be maintained as accurately as in separate single-target searches. They suggest that baggage X-ray security screeners should specialize in one type of threat, or be trained to conduct 2 independent searches, 1 for each threat item.

Keywords: dual-target search, eye movements, airport security, color guidance, X-ray images

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Visual search for a single target is well understood in terms of how target features are represented in order to guide search, with search guidance using a mental representation of the target (e.g., round and rectangular) to guide attention to those items in the display that contain those features (e.g., Quinlan & Humphreys, 1987; Wolfe, Cave, & Franzel, 1989). In practice, however, many visual searches have multiple targets or target categories; for example, in airport security search, screeners must search X-ray images of baggage for multiple types of threat item (e.g., guns, knives, and explosives). There is a cost in performance when searching for two targets relative to single targets (e.g., Menneer, Barrett, Phillips, Donnelly, & Cave, 2007) with simple stimuli, X-ray image stimuli, and after practice (e.g., Menneer, Cave, & Donnelly, 2009). In search for simple targets (e.g., color patches), eye movements have shown the cause of this cost to be reduced attentional guidance of eye movements toward target-color objects in dual- versus single-target search (Stroud, Menneer, Cave, & Donnelly, 2012; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011). These studies on guidance reinforce recommendations that targets in airport security screening be split across screening per-

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sonnel, with each screener specializing in search for one type of threat at a time. However, the relevance of these conclusions to security screening can be questioned because the reduction in color guidance has been established only in unpracticed search for simple stimuli that might miss the complexities and variation present in X-ray images. In addition, these findings about guidance might not hold for highly practiced searchers (e.g., screening personnel).

The current research tested whether reduction in color guidance underlies the cause of the dual-target cost in search of X-ray images, as it does for simple stimuli. This research goes beyond previous studies on dual-target search in three key ways: (a) by examining guidance for categorically defined targets, (b) by using overlapping X-ray images, and (c) by exploring the role of practice on search guidance.

To understand the dual-target cost and the importance of attentional guidance in dual-target search, mechanisms for single-target search must first be understood. When the search target does not have a unique feature, single-target search must be guided by a mental representation that includes a combination of key target features (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). This top-down system avoids locations that contain no target features and prevents search from being completely random and unguided (Wolfe et al., 1989). However, disjunctive guided search for either of two targets requires that features of both targets are mentally represented. When two targets have different features in the same dimension, performance in search is lower than combined performance across two independent single-target searches. This dual-target cost has been demonstrated for consistent targets (i.e., targets that do not vary from one trial to the next; Menneer et al., 2007; Menneer, Donnelly, Godwin, & Cave, 2010) as well as for targets drawn from two different categories (Menneer et al., 2009). The dual-target performance cost remains after practice and occurs with both simple and X-ray image stimuli (Menneer et al., 2009, 2010), although in these circumstances it is not known whether the cost is caused by a reduction in search guidance. Dual-target search can sometimes be efficient if a mental representation of the target is not required for guidance or if a single representation can specify the targets without including distractors (Barrett, Menneer, Phillips, Cave, & Donnelly, 2003; D'Zmura, 1991; Menneer et al., 2009; Quinlan & Humphreys, 1987; Treisman, 1988; Treisman & Gelade, 1980).

Eye tracking was employed in the current research because it provides a tool for investigating search guidance by revealing the features that participants are fixating and therefore the features that are driving search (Findlay, 2004). In previous experiments with consistent color–shape conjunction targets of different colors, eye tracking revealed a reduction in color guidance that leads to the fixation of some distractors that are dissimilar in color to either target (Stroud et al., 2011, 2012). Such overfixation of non–target-color distractors, and hence relative underfixation of target-color distractors, underlies the cost in performance in dual-target search relative to two separate single-target searches.

In these earlier experiments, targets were defined by precise single values of color and shape, whereas the current research used X-ray image stimuli that are complex and heterogeneous. The role of color guidance might be different in the dual-target cost for X-ray images than in simple color–shape conjunctions for the following reasons. Threat-item targets are categorically defined (e.g., metal threats, improvised explosive devices [IEDs]), with features more common in some categories than in others (e.g., blue is a common color in the category of metal threats), and with variation within the categories (e.g., metal threats can vary from very dark blue to light blue, and metal-threat handles can vary in color depending on the material). Guidance can be effective in search for categorically defined targets (Yang & Zelinsky, 2009), but search for multiple categories sometimes relies on properties of specific objects (Smith, Redford, Washburn, & Taglialatela, 2005), and performance is little above chance, even when the target categories are well practiced (Smith, Redford, Gent, & Washburn, 2005). For X-ray images, there is additional variation within categories caused by object overlap. Color in X-ray images results from atomic density. When objects overlap, the color at a given point is contributed to by all the objects at that point, such that component "colors" are averaged. Such averaging may reduce the efficacy of the target representation(s) and reduce guidance. If guidance is reduced, exhaustive search might be required to determine the presence or absence of a target irrespective of the number of targets being sought. In other words, for complex stimuli, single-target search might be so unguided that there is no cost in guidance to including an additional target. Therefore, it is important to establish that previous findings of guidance and the dual-target cost in simple stimuli also underlie the cost in more complex X-ray image target categories, and overlapping X-ray images in particular.

Previous studies have explored the effect of practice on the dual-target cost, but have not examined the relationship between practice and guidance. Practice generally improves guidance, with searchers learning to ignore salient but irrelevant features in images (Nodine, Kundel, Lauver, & Toto, 1996). Inefficient search for multiple targets can become efficient after practice (Kaplan & Carvellas, 1965; Neisser, Novick, & Lazar, 1963; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). These earlier experiments used familiar alphanumeric characters, the mental representations of which are perhaps relatively easy to learn. Further studies have also shown that practice can improve performance in visual search for categorically defined X-ray image targets, and some of this improvement can generalize to previously unseen category exemplars, thus providing evidence against purely specific token effects for X-ray targets (McCarley, Kramer, Wickens, Vidoni, & Boot, 2004; Menneer et al., 2009). However, the dual-target cost does remain after many hours of practice, both for X-ray images (Menneer et al., 2009) and color–shape conjunctions (Menneer et al., 2010). Previous dual-target search research has examined eye movements over only a small number of trials (Stroud et al., 2011, 2012). Tracking eye movements throughout hours of X-ray image search allowed us to investigate how color guidance changes with practice. It determined whether the dual-target cost found with X-ray images after practice is due to poor guidance rather than some other cause (e.g., target recognition).

The aims of this study were threefold. First, we measured the dual-target cost of searching in X-ray images. We determined whether the cost survives when searching *overlapping* X-ray images. This cost was measured and tracked over practice by comparing response time and accuracy across dual- and single-target searches.

Second, we sought to establish whether reduced color guidance contributes to a dual-target cost in search for categorically defined targets in complex X-ray images. Prior to examining color guidance, we also examined the basic eye-movement measures to

better understand the process underpinning dual-target search. There are at least two possible strategies for dual-target search (e.g., Menneer et al., 2010). One possibility is simultaneous search, in which participants make the same fixations as in single-target search and with each fixated object being compared with both target representations. In this case, the number of fixations should be the same across single- and dual-target searches, but fixation durations (i.e., time spent fixating an object) should increase for dual-target search over single-target searches to allow time for comparison with both target representations. An alternative strategy would be to conduct two separate sequential single-target searches, one for the first target (e.g., metal threats) followed by one for the other target (e.g., IEDs). This strategy would result in similar fixation durations but more fixations and refixations to objects in dual-target search than single-target searches. To understand the role of color guidance in dual-target search, we compared the probabilities of fixating specific colors and objects across single- and dual-target searches. Given the previous results with simple stimuli, a priori we expected that dual-target search would result in fewer target-color objects being fixated and more non–target-color objects being fixated, compared with single-target searches.

Lastly, the eye tracking in the current study should show more clearly how color guidance develops and changes as searchers gain experience with simultaneous search for metal threats and IEDs. Given previous research with categorical stimuli, we predicted that practice would improve color guidance, and expected the results to show how this improved guidance is manifest and how it changes the dual-target cost.

To preview the results, more targets were missed in dual-target search than single-target searches, particularly when images were overlapping. This pattern was caused by reduced guidance in dual-target search, with participants making fewer fixations on target-color items and disproportionately more on non–target-color items compared with the combination of fixations across separate single-target searches. This pattern held after practice.

Method

Participants completed 16 sessions (5,376 trials) within 40 days on search of baggage X-ray images, with 26 participants specializing in dual-target search and 18 participants specializing in single-target search (either single-metal-threats-search or single-IEDs-search). Eye movements were recorded in every fifth session, including the first and last sessions, to determine the number of fixations made in each type of search and the frequency of fixation to objects of each color (orange, green, blue-black, mixed).

Participants

Forty-four participants (34 women, 10 men; M_{age} = 23 years, SD = 4.0, range = 18–36 years) took part in the experiment. Most participants were university students (undergraduate and postgraduate). All were recruited by word of mouth or via a university experiment participation sign-up Website. Two additional participants were originally recruited, but were excluded from the analyses because their response times (RTs) increased throughout the experiment to the point where their median RT was +3 SD away from the mean of medians for the rest of the participant group in the final experimental session. All participants had self-reported normal or corrected-to-normal vision. Normal color vision was confirmed with the Ishihara color-blindness test plates. Some of the participants had prior experience with visual search tasks, but not with X-ray stimuli, and all were unaware of the purpose of the experiment. Participants received payment for their participation and were fully informed about the nature of the task. Participants were recruited and tested across two locations: University of Southampton (26 participants) and University of Massachusetts (20 participants). For each condition, half of the participants were tested at the University of Southampton and half at the University of Massachusetts, except for dual-target search in which 16 were from Southampton and 10 from Massachusetts. More participants were recruited in dual-target search than in single-target searches to develop experienced dual-target searchers for a future, currently unreported, experiment. No significant differences between locations were revealed via 180 uncorrected t tests for RT, accuracy, and eye-movement measures for target-present and target-absent trials and all sessions (ps $\geq$ .08). The most significant result (p = .08) occurred for the comparison of RT in Session 15 (the last non-eye-tracking session) on target-absent trials, with participants at Southampton being faster than those at Massachusetts. All other comparisons gave $p > .10$.

Apparatus

Sessions with nonoverlapping images and eye tracking (Sessions 1, 6, 11, and 16). In Southampton, stimuli were displayed on a Dell precision 390 computer with a ViewSonic P227f monitor. Eye movements were recorded using an EyeLink 1000 system with a sampling rate of 1000 Hz interfaced with a Dell precision 390 computer. In Massachusetts, the stimuli were presented on a 17-in. Vision Master Pro 514 Iiyama CRT monitor attached to a Pentium 166 MHZ computer interfaced with an EyeLink II eye-tracking system with a sampling rate of 250 Hz. In both locations, the tracker was calibrated within a maximum of 0.5° visual angle error; viewing was binocular, although only the participant's right eye was tracked; both pupil and corneal reflections were tracked; and a chin rest was used to minimize head movements at a viewing distance of 57 cm from the display. Default and recommended settings were used for the EyeLink parameters to define the fixations and saccades. A saccade onset was demarcated when the spatial separation of samples indicated an eye movement with a velocity that exceeded 30°/s or an acceleration that exceeded 8000°/s^2. If these criteria were not met, then successive samples were assumed to compose the current fixation. Responses were recorded using a Microsoft gamepad controller in both locations.

Sessions with overlapping images and no eye tracking (Sessions 2–5, 7–10, and 12–15). Custom software, written in C with the Vision Shell routines (Raynald Comtois), was run on an Apple Mac G4 computer. Stimuli were presented on a Formac ProNitron 19/600 monitor in Southampton and a NEC Multisync FE990 monitor in Massachusetts. Both monitors were set at a resolution of 600 × 800 pixels with a refresh rate of 100 Hz. Responses were recorded using a Cedrus RB-610 button box in Southampton and a Cedrus RB-530 response pad in Massachusetts. Both button boxes were connected to the Apple Mac via the USB port. Participants viewed the monitor using a chin rest at a distance of 57 cm in a moderately lit room.

Stimuli

The stimulus set comprised more than 1,400 X-ray images of baggage and threat items provided by the U.S. Transportation Security Administration. There were 44 types of typical baggage objects such as books and CD players, each containing a varying number of exemplars. Each exemplar had up to five images from different viewpoints: 0° (canonical view), 45° and 90° in the *x*-plane, and 45° and 90° in the *y*-plane. Each image could be presented with 0°, 90°, 180°, or 270° rotation in the picture plane, providing 20 possible orientations altogether. Images were presented in 32-bit color and subtended 0.7° to 28.0° visual angle. The color of the images ranged across orange, green, and blue, and was dependent on the atomic number, atomic density, and thickness of the medium through which the X-ray traveled (e.g., Figure 1). Prior to the experiment, all images were viewed by six researchers and placed into one of four color categories, which were mixed, orange, green, and blue-black. The choice was dependent on the predominant color in the image, and if there was no predominant color, it was categorized as mixed. The modal category across the six responses was selected for each object. This categorization allowed us to determine the colors fixated by participants in different types of search. The color distributions for all targets and distractors are shown in Table 1. All stimuli were presented on a white background.

Target sets were 39 metal threats (19 guns and 20 knives), each with 20 possible orientations, and 69 IEDs, which did not vary in viewpoint but were rotated in the monitor plane. More IEDs were used than metal threats to compensate for the lack of viewpoint rotations. The distribution of exemplars was representative of each type, such that there were more common items than unusual ones, and extreme examples were included to demonstrate the variety of each type. Typically, IEDs were characterized by orange explosive or mixed-color electronics and metal-threat items by blue metal. However, there were some deviations from these colors, depending on the exact nature of each object's material.

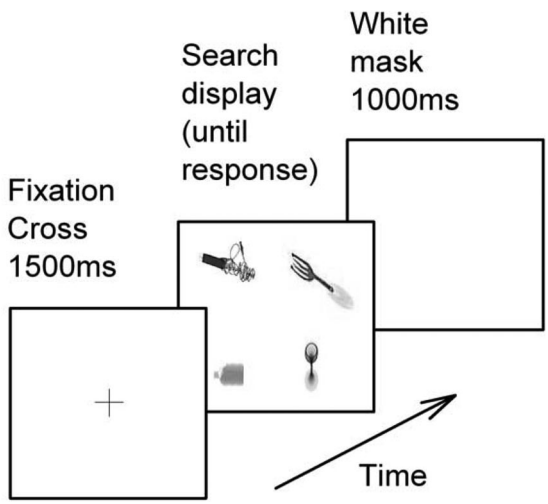

Figure 1. Trial sequence and example stimuli. The images are a curling iron that is primarily blue (top left), a blue-black kitchen fork with a pale orange handle (top right), a green wine glass (bottom right), and an orange bottle (bottom left). From "The Cost of Searching for Multiple Targets: Effects of Practice and Target Similarity," by T. Menneer, K. R. Cave, and N. Donnelly, 2009, *Journal of Experimental Psychology: Applied, 15*, p. 128. Copyright 2009 by the American Psychological Association. Adapted with permission. A link to a color version of this figure is available in the supplemental materials.

Table 1
Percentage of Images of Each Color in Each Object Category

Object category	Blue-black	Orange	Green	Mixed
Guns	99	1	0	0
Knives	85	6	2	7
IEDs	4	9	7	80
Distractors	30	19	11	40

Note. From "The Cost of Searching for Multiple Targets: Effects of Practice and Target Similarity," by T. Menneer, K. R. Cave, and N. Donnelly, 2009, *Journal of Experimental Psychology: Applied, 15*, p. 128. Copyright 2009 by the American Psychological Association. Reprinted with permission. IEDs = improvised explosive devices.

Nonoverlapping images. For eye-tracking sessions, images did not overlap within the search array, making it possible to track eye movements to specific objects. In each nonoverlapping array, 10 items were arranged in a circle with diameter of 19.5° visual angle for Massachusetts and 23.5° for Southampton, measured to the center of the objects. Each object was scaled to fit within a rectangle of 5.0° × 4.7° for Massachusetts and 5.9° × 5.9° for Southampton. Figure 2a provides an example display. The whole display subtended a visual angle of 25.7° × 32.5° for Massachusetts and 30.5° × 40.5° for Southampton.

Overlapping images. For non-eye-tracking sessions, the search array for each trial comprised 10 objects, randomly assigned to one of 16 possible locations on a 4 × 4 virtual grid, with each displaced from the center of the location by a randomly generated distance. Objects were allowed to overlap, and the degree of overlap was increased by maintaining a white border of 4.8° minimum around the display. Overlapping colors were defined as the weighted average of the overlapping RGB values, with more weight given to darker images (smaller RGBs) such that their contribution was not overly lightened by higher RGB values. Objects were not resized unless it was necessary to do so to fit within the dimensions of the display. Figure 2b provides an example display. The whole display subtended a visual angle of 27.3° × 36.5° for Massachusetts and 26.2° × 34.8° for Southampton.

Procedure

Participants completed 16 sessions of search for threat items, with the search type varied across three participant groups: (a) eight participants (after two exclusions) conducted single-target search for metal threat items (guns and knives), (b) 10 participants conducted single-target search for IEDs, and (c) 26 participants conducted dual-target search for both metal threats and IEDs. A target was present on half of the trials within each session. Search type was a between-participants factor to allow participants to focus on and practice only one type of search.

Eye movements were tracked every five sessions including the first session to serve as a baseline (Sessions 1, 6, 11, and 16). Each eye-tracking session comprised 192 trials and lasted approximately 15–30 min. Participants conducted search for their assigned target

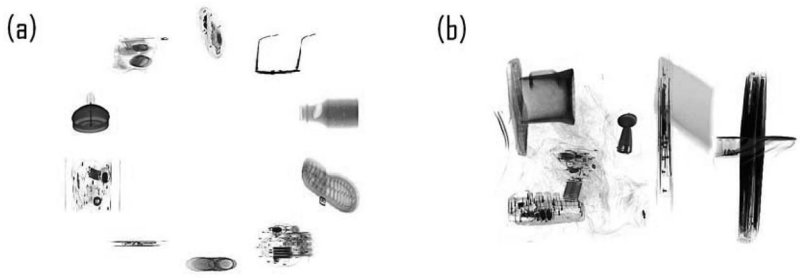

Figure 2. Example target-absent displays from the nonoverlapping (eye-tracking) sessions (a) and the overlapping (non-eye-tracking) sessions (b). The overlapping image (b) is not from a Transportation Security Administration certified machine. A link to a color version of this figure is available in the supplemental materials.

type within these sessions. However, for half of the participants in each search-type group, the second half of each eye-tracking session comprised three test blocks, one for each type of search (single-metal-threat-search, single-IED-search, dual-target search). The purpose of these blocks was to examine performance on the two search types on which the participant was not practiced. The test blocks were kept to a minimum (32 trials each) so as not to provide practice for the participant. The data from test blocks are not presented in the results in order to focus on the eye-movement measures and the dual-target cost. For the other half of the participants, both halves of each eye-tracking session comprised the assigned search type.[1]

A central fixation dot was presented before each trial to allow for calibration accuracy to be checked, and was displayed until the experimenter was satisfied with the accuracy of the fixation (around 500 ms). Recalibration was conducted if the error in fixation was greater than 1°. The stimulus display was presented until a response was made.

Each non-eye-tracking session comprised 384 trials (Sessions 2–5, 7–10, and 12–15), and lasted approximately 30–50 min. Prior to each trial, a central fixation cross was presented for 1,000 ms, followed by the display, which was present until a response was made. An opportunity for a break was provided every 50 trials.

In eye-tracking and non-eye-tracking sessions, participants responded using the button box, pressing one button for a present response and another same-sized button for an absent response. Correct responses received no feedback and proceeded to the next trial, whereas incorrect responses were indicated with a beep before proceeding.

As indicated above, each participant completed the 16 sessions over a maximum of 40 days ($M = 19$ days, $SD = 6.9$), with a minimum break of 30 min between sessions. Most participants completed no more than two sessions per day, but due to practical restrictions, four participants (two single-target and two dual-target) once completed three sessions in 1 day. Eighty-one percent of sessions were completed on the same day as another session, and the mean number of days between sessions was 1.1 day.

Results

The analyses are divided into three sections: (a) dual-target cost, (b) comparing strategies for dual-target search, and (c) color guidance in dual-target search. To address the first aim, Section A presents analyses to confirm a dual-target cost in performance (RT and accuracy) with categorically defined targets in complex and overlapping X-ray images. To address the second aim, Sections B and C examine eye movements to explore search strategies and assess color guidance in dual-target search. To address the third aim, we explore the effect of practice in all sections. Some analyses are preceded by a short summary of their results.

In all analyses, Greenhouse–Geisser corrected degrees of freedom were used when the assumption of sphericity was violated. All *t* tests were post hoc, with Bonferroni correction to the *p* value, and adjusted degrees of freedom when Levene's test showed a violation of equality of variances. Effect sizes are reported using partial eta-squared and *r*.

A. Dual-Target Cost

Analyses were conducted separately for overlapping and nonoverlapping (eye-tracking) sessions. Two dependent measures of performance, RT and accuracy, were used to compare dual-target and single-target searches to test for a dual-target cost. Median RTs were calculated using correct responses only. Median RT was used to minimize effect of skew. Data were otherwise untrimmed.

To test for a cost in performance for dual-target search compared with single-target searches, we analyzed accuracy and RTs in separate analyses of variance (ANOVAs), with factors of search type (single-metal-threats, single-IEDs, dual-target), target presence (target-present, target-absent), and session (12 sessions [2–5, 7–10, 12–15] for overlapping, four sessions [1, 5, 11, 16] for nonoverlapping). Search type was a between-participants factor, and session and target presence were within-participants factors. When two *F*, *t*, and *p* values are presented, the first is from the overlapping condition and the second is from the nonoverlapping condition. See Figure 3, Figure 4, Figure 5 and Figure 6 for a summary of the data.

[1] Comparisons between those who conducted test blocks and those who did not showed no effects of test block (Fs < 2.21, $p > .145$), except for RT in the eye-tracking sessions, $F(1,38) = 5.36$, $p = .026$; number of fixations, $F(1,38) = 8.27$, $p = .007$; proportion of IAs revisited, $F(1,38) = 5.07$, $p = .030$; and probability of visiting each color, $F(1,38) = 8.03$, $p = .007$. However, for these measures, the effect of test block did not differ across search type (interactions: Fs < 1, $p > .628$).

Accuracy. For both overlapping and nonoverlapping sessions, accuracy was dependent on search type, Fs = 15.25 and 11.98, ps < .001, η_p^2s ≥ .369, with lower accuracy in dual-target search and single-IED-search than in single-metal-threat-search (ts > 2.9, p < .027, r ≥ .600), but no difference between dual-target search and single-IED-search, ts = 1.28 and 1.13, ps = .63 and .81. In the overlapping sessions, accuracy improved with session, $F(3.8, 156.7) = 37.87$, $p < .001$, $\eta_p^2 = .480$, until Session 13 (effect of session over Sessions 13–15), $F(2, 82) = 1.20$, $p = .31$. In the nonoverlapping sessions, performance improved monotonically with session, $F(2.2, 88.3) = 62.25$, $p < .001$, $\eta_p^2 = .603$. The main effect of target presence was significant in the nonoverlapping condition, $F(1, 41) = 23.09$, $p < .001$, $\eta_p^2 = .360$, in which absent trials were responded to more accurately than present trials, but not in the overlapping condition, $F(1, 41) = 2.68$, $p = .11$.

In the overlapping condition, the main effects were qualified by a trend toward an interaction between Search Type × Target Presence, $F(2, 41) = 2.98$, $p = .06$, $\eta_p^2 = .127$. On target-present trials, accuracy was lower in dual-target search than both single-target searches (ts > 3.2, p < .01, r ≥ .482), and the difference between single-target searches was not significant, $t(16) = 1.69$, $p = .11$. On target-absent trials, accuracy was lower in dual-target search and single-IED-search than in single-metal-threat-search (ts > 5.1, p < .001, r ≥ .709), whereas there was no difference between dual-target search and single-IED-search (t < 1).

In the nonoverlapping condition, the main effects were qualified by a significant Search Type × Session interaction, $F(4.3, 88.3) = 3.65$, $p = .01$, $\eta_p^2 = .151$. In general, accuracy in dual-target search was comparable to that in single-IED-search, but there was particularly low accuracy in dual-target search in Session 1. There was also a significant Target Presence × Session interaction, $F(3, 123) = 4.54$, $p = .005$, $\eta_p^2 = .100$ (see Figure 4a), which reflects rapid improvement between Sessions 1 and 6 on target-absent trials. There were no other significant interactions in either analysis (Fs < 1.1, p > .35).

These results show a clear dual-target cost on target-present trials, with more misses in dual-target search than either of the single-target searches, and a partial dual-target cost on target-absent trials with more false alarms in dual-target search than single-metal-threat-search. The lack of a difference between dual-target and single-IED-search might be caused by the difficulty of search for IEDs relative to metal threats, as revealed by the single-target search data. To establish whether there were similar differences between metal threats and IEDs within dual-target search, we calculated hit rates independently for each type of target-present trial. (Target-absent trials in dual-target search can-

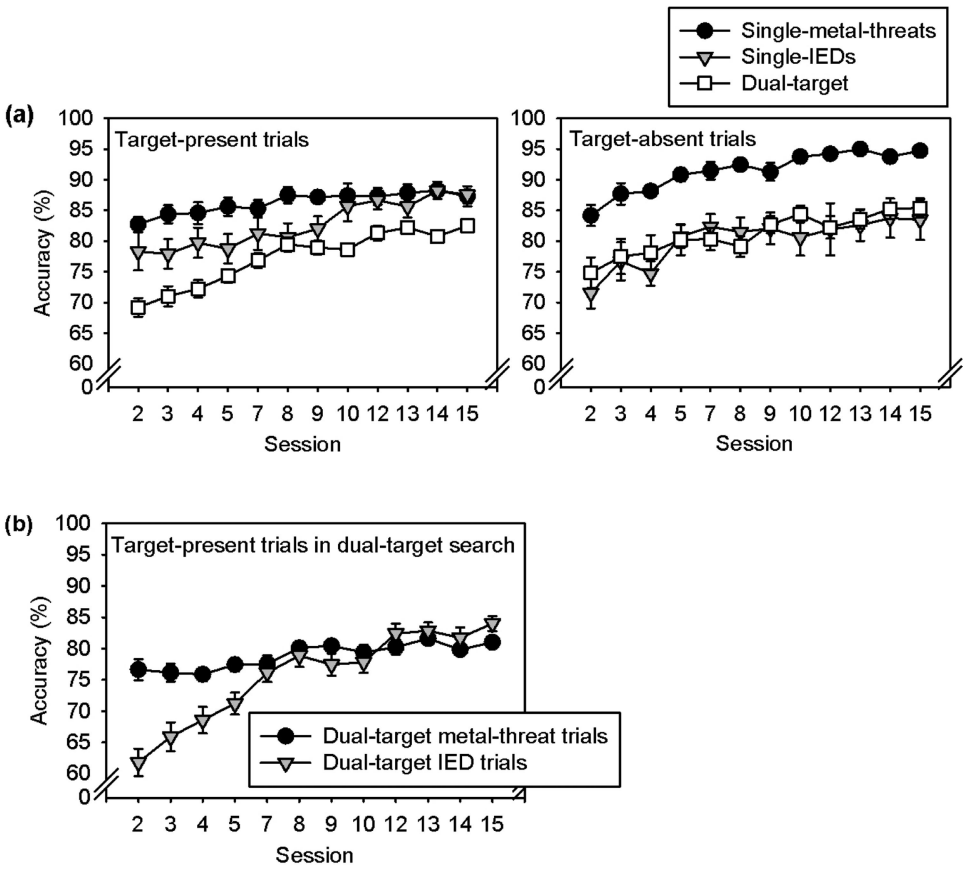

Figure 3. (a) Accuracy for each search type (single-metal-threats, single-improvised-explosive-devices [IEDs], dual-target) and each overlapping (non-eye-tracking) session, for target-present (top left panel) and target-absent (top right panel) trials. (b) Accuracy for metal threats and IEDs within dual-target search only. Error bars indicate the standard error.

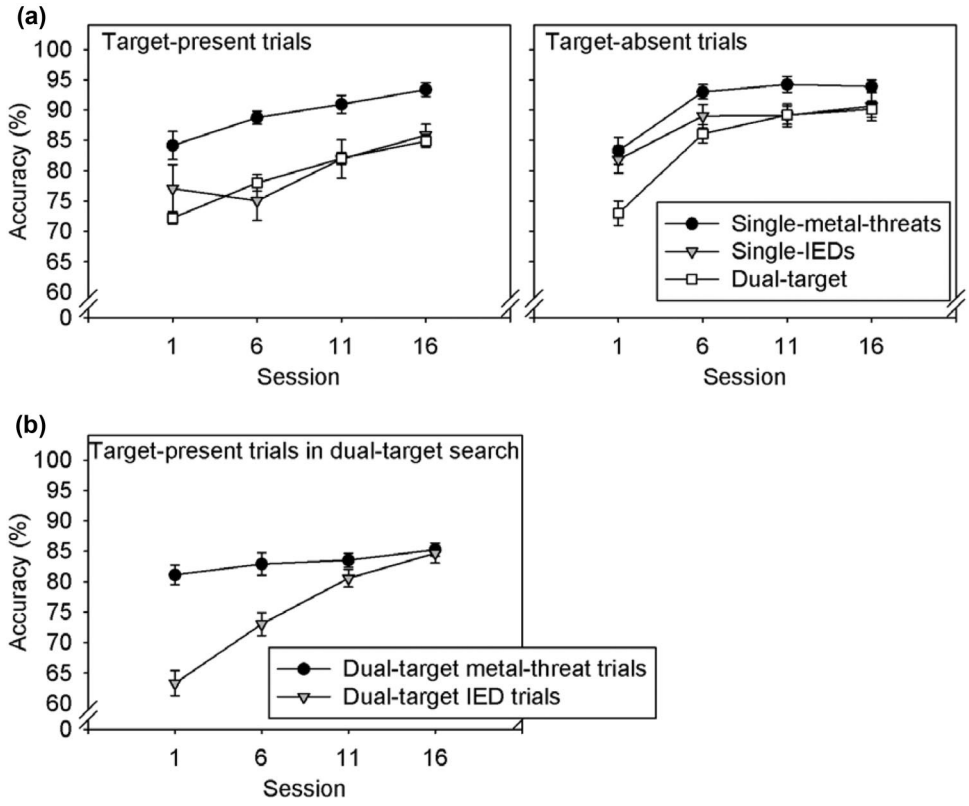

Figure 4. (a) Accuracy (with standard error bars) for each search type (single-metal-threats, single-improvised-explosive-devices [IEDs], dual-target) and each nonoverlapping (eye-tracking) session, for target-present (top left panel) and target-absent (top right panel) trials. (b) Accuracy for metal threats and IEDs within dual-target search only.

not be assigned to metal threat or IED search.) Overall, hit rate was higher for metal threats than IEDs, Fs = 7.14 and 29.54, ps = .01 and < .001, η_p^2s = .222 and .542, but there was a significant interaction with session, $F(5.6, 139.5) = 13.43$, $p < .001$, $\eta_p^2 = .349$, and $F(3, 75) = 13.49$, $p < .001$, $\eta_p^2 = .351$. In both cases, hit rates converged over sessions. In the last session of the overlapping condition, IED hit rate was actually slightly higher than metal threat hit rate, $F(1, 25) = 5.38$, $p = .03$, $\eta_p^2 = .177$ (see Figure 3b). This result demonstrates that in dual-target search, practice can allow search for the more difficult target (IEDs) to become as

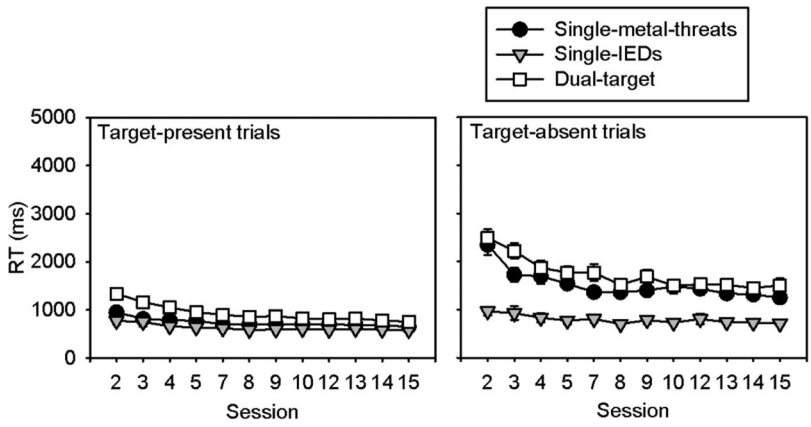

Figure 5. Median response times (RTs; with standard error bars) for each search type (single-metal-threats, single-improvised-explosive-devices [IEDs], dual-target) and each overlapping (non-eye-tracking) session, for target-present (left panel) and target-absent (right panel) trials.

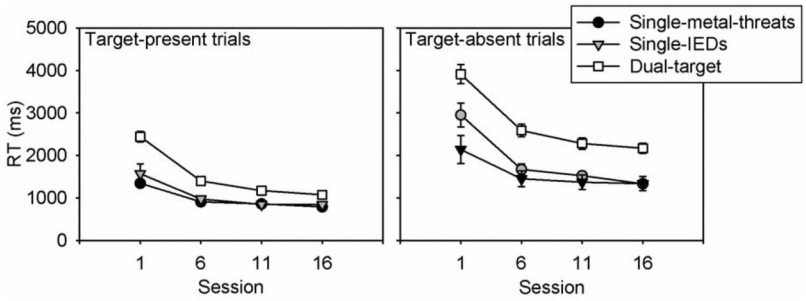

Figure 6. Median response times (RTs; with standard error bars) for each search type (single-metal-threats, single-improvised-explosive-devices [IEDs], dual-target) and each nonoverlapping (eye-tracking) session, for target-present (left panel) and target-absent (right panel) trials.

accurate as search for the other target (metal threats; see Figure 4b).

Response time. RT depended on search type, Fs = 14.19 and 18.58, ps < .001, η_p^2s ≥ .409. For overlapping images, dual-target search was slower than single-IED-search, $t(33.3) = 6.83$, $p < .001$, $r = .764$, but not single-metal-threats-search, $t(28.67) = 2.17$, $p = .11$, and single-metal-threat-search was slower than single-IED-search, $t(16) = 5.45$, $p < .001$, $r = .744$ (see Figure 5). With nonoverlapping images, RTs were longer in dual-target search than both single-target searches (ts > 4.9, $p < .001$), with no difference between the single-target searches ($t < 1$; see Figure 6).

RT decreased with session, $F(3.9, 159.3) = 28.3$ and $F(1.3, 51.6) = 73.38$, ps < .001, η_p^2s ≥ .408. For overlapping images, the effect of session disappeared after Session 13 (effect of session over Sessions 13–15), $F(1.7, 70.8) = 1.32$, $p = .27$. RT was slower on target-absent trials than on target-present trials, $F(1, 41) = 63.32$ and 126.94, ps < .001, η_p^2s ≥ .607.

All pairwise interactions were significant (Fs > 2.41, $p < .02$, $\eta_p^2 \geq .105$). With regard to the dual-target cost, on target-present trials, dual-target search was slower than both single-target searches over all sessions including, importantly, the last session (ts > 3.47, $p < .01$, $r \geq .556$). The pattern on target-absent trials varied across overlapping and nonoverlapping sessions. For overlapping images, dual-target search was slower than single-IED-search, $t(33.9) = 6.63$, $p < .001$, $r = .754$, but not single-metal-threat-search, $t(32) < 1$, and these relationships remained the same in the last session, $t(30.9) = 5.05$, $p < .001$, $r = .672$, and $t(25.9) = 1.32$, $p = .60$, respectively. For nonoverlapping images, the dual-target cost remained in the final session, with longer RTs in dual-target search than both single-target searches (ts > 3.8, $p < .001$, $r \geq .552$).

For overlapping images, termination of single-IED-search on target-absent trials was faster than single-metal-threat-search, across all sessions, $t(16) = 5.84$, $p < .001$, $r = .825$, including the last session, $t(16) = 4.24$, $p = .001$, $r = .728$. The lack of difference between single-metal-threats-search and dual-target search on target-absent trials reflects slow RTs in single-metal-threats-search, indicating that participants are conducting a thorough search, and hence achieving the high level of accuracy observed in single-metal-threats-search.

Summary of dual-target cost. These analyses demonstrate a dual-target cost, with more misses in dual-target search than single-target searches, more false alarms than in single-metal-threat-search, longer RTs than both single-target searches for nonoverlapping images, and longer RTs than single-IED-search for overlapping images. For overlapping images, there is evidence of a speed–accuracy trade-off in single-metal-threat-search with long RTs and high accuracy and in single-IED-search with short RTs and low accuracy.

Performance in metal threats search. Search for metal threats gave high accuracy, but, on target-absent trials, responses were as long as for dual-target search when objects overlapped. Metal threats are likely to be more salient in overlapping X-ray images than IEDs are because the coloring is more consistent and the metal is dense so that it will show through most overlapping materials. However, variations in viewpoint can make metal threats difficult to identify once located. Participants may direct their eyes to the metal objects fairly quickly, but may then take their time identifying it as a target or a distractor.

Performance in IED search. Search for IEDs tended to result in faster responses and lower accuracy, particularly on target-absent trials. These results indicate that IEDs are more difficult to locate and identify than guns and knives. The IED search performance contrasts with most other visual search experiments in that RTs are so fast despite the low accuracy. We might expect participants to delay search termination, given the high number of misses and false alarms, especially after hours of feedback and practice that would allow adjustment of the search strategy. Possible reasons for the differences between IED search and metals search are presented at the end of the Discussion section.

B. Comparing Strategies for Dual-Target Search

Before addressing the second aim of determining the role of guidance in dual-target search, we need to first examine the basic underlying eye movements that contribute to the guidance process, but do not themselves define it. This section presents those analyses to better understand the underlying search strategy employed in dual-target search. The following subsection summarizes the possible strategies and the findings. The subsequent three subsections provide details on the analysis method and data trimming, the standard eye-movement measures including fixation duration, and visits and revisits to objects in the display.

Summary of dual-target strategies. If dual-target search is implemented as a simultaneous search with each object fixated

once and compared with both target representations during that fixation, then we would expect increased fixation durations compared with single-target searches. However, there was no evidence of a dual-target cost for fixation duration. Alternatively, if dual-target search comprises two separate single-target searches, one for metal threats and one for IEDs, we would expect more revisits in dual-target search than the single-target searches. This pattern was observed early in the experiment. However, if the target representations driving search become accurate and effective with practice, and are able to guide search only to items matching the target descriptions, it is unlikely that the set of objects examined when searching for metal threats will overlap with that examined when searching for IEDs because the two target types differ in color and form. In this case, there will be as many revisits in dual-target search as there are in single-target searches. After practice, there was no difference in revisits, suggesting that participants conducting dual-target search have been able to strengthen their target representations enough that there was little overlap between metal threat items of interest and IED items of interest. Details are described in the following subsections.

Analysis and data trimming methods. Unless otherwise stated, each measure was analyzed with factors of search type (single-target-metal-threats, single-target-IEDs, dual-target), target presence (present, absent), and session (1, 6, 11, 16), in which search type was a between-participants factor, and session and target presence were within-participants factors.

All measures, except saccade onset latency, were calculated over correct trials only. Eye-movement measures were calculated with the following fixations excluded: first fixation (i.e., prior to launch of first saccade), the fixation coinciding with the press of the response button and all subsequent fixations, extremely short (80 ms), and extremely long (1,200 ms) fixations.

Because some fixations fell short of the actual stimulus objects, interest areas (IAs) were defined as circles with radii of 4.2° from the center of each object. This value was chosen to be the maximum distance from the object center to the edge of the object. This IA range was large enough for adjacent IAs to overlap, but any fixation that lay within an overlap area was assigned to the closer object. Separate analyses based purely on fixations on the actual object images (strict IAs) showed broadly similar patterns of results to those reported here. There were two differences, which are noted in the text. The reported analyses, based on extended IAs, suffer from fewer missing data than analyses based on strict IAs. Data are presented in Figure 7 and Figure 8.

Standard eye-movement measures. There were no significant effects or interactions for saccade onset latency (M = 168 ms).

Fixation duration (M = 181 ms) decreased with session, $F(1.8, 75.1) = 49.70$, $p < .001$, $\eta_p^2 = .548$, but there was no effect of search type, $F(2, 41) = 1.60$, $p = .22$, or target presence, $F(1, 41) = 2.83$, $p = .10$. Interactions did not reveal any evidence for a dual-target cost, so are not reported here.

The number of fixations followed a very similar pattern to RT, including a dual-target cost, $F(2, 41) = 19.70$, $p < .001$, $\eta_p^2 = .490$, of more fixations in dual-target search than the single-target searches ($ts > 3.8$, $p < .001$, $r \geq .566$; Ms = 5.8, 4.9, and 8.4, for metal threats, IEDs, and dual-target searches, respectively). The dual-target cost remained in the final session, with more fixations in dual-target search than both single-target searches for both target-present and target-absent trials ($ts > 4.7$, $p < .001$, $r \geq .590$).

Proportion of IAs visited and revisited. The proportion of IAs that were visited was calculated as the number of fixated IAs of the 10 IAs present in each display. Only effects relating to search type are reported. The proportion of IAs visited was dependent on search type, $F(2, 41) = 34.26$, $p < .001$, $\eta_p^2 = .626$, with a dual-target cost ($ts > 5.07$, $p < .001$, $r \geq .668$), and no significant difference between the single-target searches, $t(16) = 1.83$, $p = .26$. All interactions were significant ($Fs > 2.81$, $p < .04$, $\eta_p^2 \geq .121$), but in the last session, the dual-target cost remained on both target-present trials and target-absent trials ($ts > 4.34$, $p < .001$, $r \geq .591$).

The proportion of IAs that were visited twice or more revealed more revisits in dual-target search than in single-IED-search, $t(31.9) = 4.40$, $p < .001$, $r = .614$, but no significant difference between dual-target search and single-metal-threats-search, $t(32) = 2.01$, $p = .16$. There was no difference between the single-target searches, $t(16) = 1.55$, $p = .43$. All interactions were significant ($Fs > 2.42$, $p < .05$, $\eta_p^2 \geq .105$). Critically, with respect to these interactions, any evidence of a dual-target cost disappeared by the last session for both target-present and target-absent trials ($ts < 2.0$, $p > .24$).

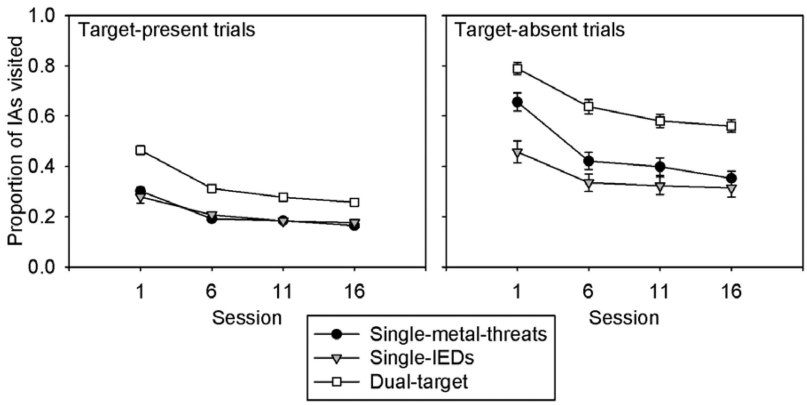

Figure 7. Mean proportion of interest areas (IAs; with standard error bars) that were visited per trial, calculated as the number of IAs fixated of the 10 IAs present in each display. IED = improvised explosive device.

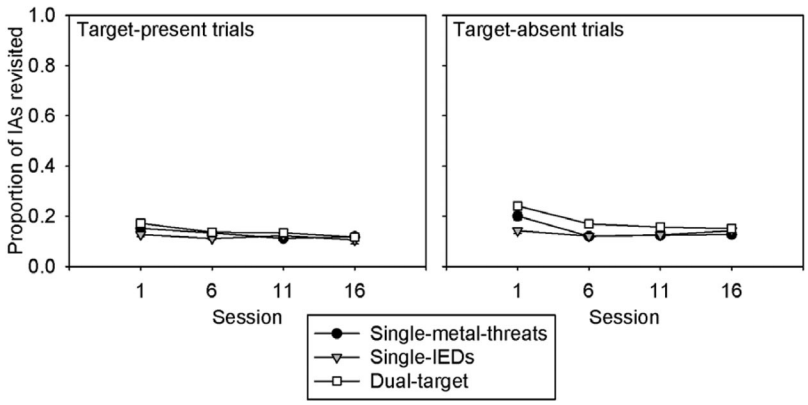

Figure 8. Mean proportion of interest areas (IAs; with standard errors) that were revisited per trial, calculated as the number of IAs revisited of the 10 IAs present in each display.

C. Color Guidance in Dual-Target Search

This section follows from Section B to complete the second aim by determining the role of color guidance in the dual-target cost. If color information is less useful in guiding dual-target search than single-target search, then we would expect dual-target search to result in fewer fixations to target-color objects and/or more fixations to non–target-color objects. Such a result would indicate that color is not represented as precisely in dual-target search as in single-target searches, and therefore the target representations are not able to guide search as effectively.

Two possible strategies for dual-target search (simultaneous search vs. two separate searches), as described in Section B, are again considered in these analyses. The probabilities of fixating given colors in dual-target search are first compared with the separate single-target searches and then compared with the combined probabilities in single-target searches.

The findings are key to the role of guidance in dual-target search. First, more fixations were made to nontarget colors in dual-target search than in each single-target search alone. Second, fewer fixations were made to target-color objects in dual-target search than in both single-target searches combined. These findings suggest that guidance is reduced in dual-target search, thereby preventing targets from being located as effectively as in single-target searches.

Comparing dual-target search with separate single-target searches. The probability of visiting each color was calculated as the number of items of a given color that were fixated once or more during a trial as a proportion of the number of items of that color that appeared in that trial. The mean probability was then calculated across trials that contained this color. The calculation differs from that in previous research (Stroud et al., 2011, 2012). In the current calculation, the probability was calculated for each trial and then averaged, rather than being calculated across all trials. The main reason for this change was that there were only four color categories in the current experiment, compared with 16 in the previous studies. The low number of colors means that within a given trial there are likely to be multiple objects of a given color, but the numbers will vary from trial to trial, causing the bottom-up influences to change, therefore influencing the objects that are fixated. Because a given object may be treated differently depending on the rest of the objects in the trial, the probability in this study was calculated to give equal weight to each trial rather than equal weight to each object (as was the case for previous studies).

The probabilities are presented in Figure 9 and were analyzed in a 4 (color: blue-black, orange, mixed, green) × 3 (search type: single-target-metal-threats, single-target-IEDs, dual-target) × 2 (target presence: present, absent) × 4 (session: 1, 6, 11, 16) ANOVA. The results reported focus on effects of, and interactions with, color.

The effect of color was significant, $F(2.5, 100.6) = 146.31$, $p < .001$, $\eta_p^2 = .781$. Blue-black and mixed items had the highest probability of fixation, with no difference between them ($t < 1$), both higher than orange ($ts > 3.23$, $p < .01$, $r \geq .442$) and both higher than green ($ts > 6.02$, $p < .001$, $r \geq .677$). There was no significant difference between orange and green items, $t(43) = 1.83$, $p = .44$.

There were five significant interactions involving color ($Fs > 2.27$, $p < .02$, $\eta_p^2 \geq .100$). Color interactions involving session were either not significant or disappeared after the first session, and the final session analysis is presented below. The remaining significant two-way interactions were embedded in the three-way interaction Color × Search Type × Target Presence, $F(5.0, 10.3) = 22.00$, $p < .001$, $\eta_p^2 = .518$.

Comparing single-target searches, more blue-black items were visited in single-metal-threat-search than single-IED-search, $t(16) = 18.45$, $p < .001$, $r = .977$, and more orange items were visited in single-IED-search than in single-metal-threats-search, $t(16) = 8.18$, $p < .001$, $r = .898$. There were no differences for mixed and green items between single-target searches ($ts < 2.37$, $p = .37$).

With regard to dual-target search, the same number of blue-black items were visited as single-metal-threats-search ($t < 1$) and the same number of orange items were visited as in single-IED-search, $t(34) = 1.95$, $p = .72$. By themselves, these fixation rates for blue-black and orange suggest that dual-target search comprises a single-metal-threat-search and a single-IED-search, with colors visited in dual-target search being accounted for by those visited in the two single-target searches. However, the probability of fixating mixed items and green items was higher in dual-target

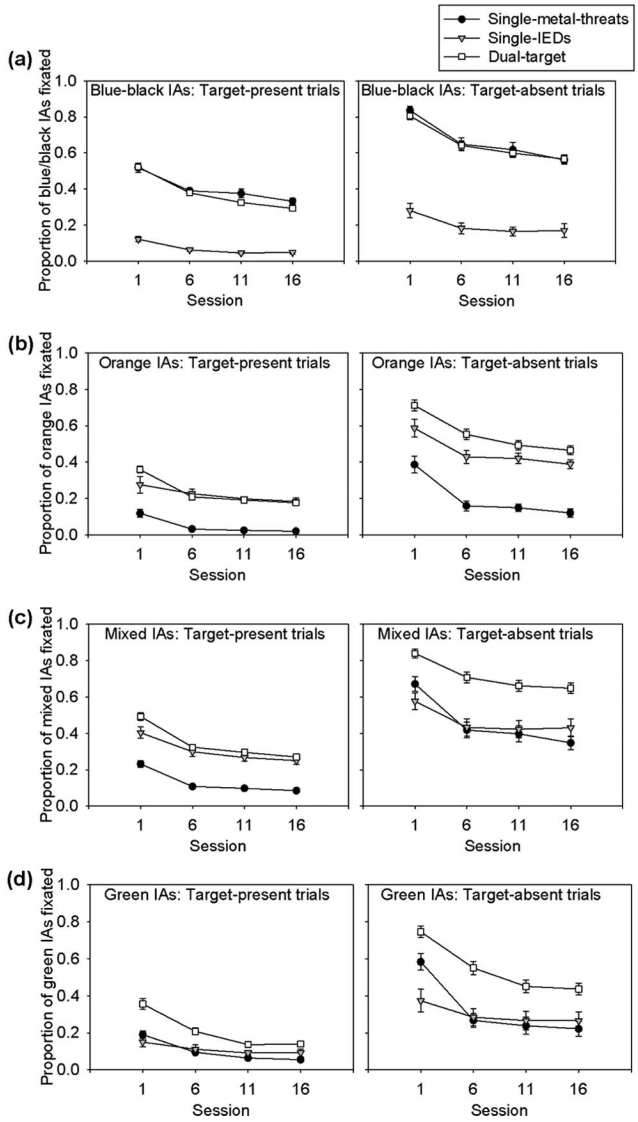

Figure 9. The probability of fixation (with standard error bars) on different color interest areas (IAs) for single-metal-threat-search, single-improvised-explosive-devices (IEDs) search, and dual-target search across target-present and target-absent trials.

search than in both single-target searches ($ts > 4.17$, $p < .001$, $r \geq .594$), suggesting that distractors are visited in dual-target search that are not visited in single-metal-threat-search. This possibility is investigated later, with further analyses on the probabilities of fixating individual distractors.

In the final session, this pattern of results held for both target-present and target-absent trials, except for two major differences on target-present trials: More mixed items were visited in single-IED-search than single-metal-threat-search, $t(16) = 6.82$, $p < .001$, $r = .863$, and the numbers of mixed and green items visited in dual-target search were the same as those in single-IED-search ($ts < 2.04$, $p > .58$, on target-present trials). The dual-target cost for mixed and green items remained on target-absent trials. In the analyses on strict IAs, for the final session, there was no significant difference in visits to green items between dual-target and single-IED-search for target-absent trials ($p = .16$).

In sum, target presence can be recognized after practice, such that similar items are visited in single- and dual-target search, and no more items need to be visited in dual-target search before the target is found. However, target uncertainty in dual-target search prolongs search beyond that required for single-target search when the target is absent.

Comparing dual-target search with two combined single-target searches. In this section, we test further the hypothesis that the dual-target search is simply the sum of two independent single-target searches, by combining the fixation probabilities across the single-target searches at the level of the individual image before comparing this probability with dual-target search. For the above measures, this combination was not possible because of the between-participants design.

The key finding is that the results (see Table 2) demonstrate a reduction in guidance in dual-target search, as shown in previous research (Stroud et al., 2011, 2012), but it is also accompanied by an overall reduction in fixation rates compared with two combined single-target searches. The result is an underfixation to target-color items in dual-target search and, proportionately, an overfixation to non–target-color items.

The probability of fixation was calculated for each distractor image in single-metal-threat-searches, single-IED-searches, and dual-target searches as the number of times the distractor was fixated once or more out of the number of times it was presented. Targets were not included because every target type was not present in all three search types. To compare the probability of fixation for all distractors across single- and dual search types, we compared the Or probabilities across single-target searches with the probabilities in dual-target search. Or probability for nonmutually exclusive events was calculated for each distractor, D, using the following formula:

$$[p(\text{fixate D})_{\text{single-metal-threats}} + p(\text{fixate D})_{\text{single-IEDs}}] - [p(\text{fixate D})_{\text{single-metal-threats}} * p(\text{fixate D})_{\text{single-IEDs}}],$$

where p(fixate D) is the probability of distractor D being fixated, regardless of participant.

The probabilities were analyzed in a 4 (color: blue-black, orange, mixed, green) × 2 (number of targets: single-target, dual-target) × 2 (target presence: present, absent) × 4 (session: 1, 6, 11,

Table 2
Mean Probability of Fixating Distractors

	Target-present			Target-absent		
Target presence	STS	DTS	t	STS	DTS	t
Blue-black	.30	.29	<1.00	.72	.66	7.40*
Orange	.26	.23	2.25	.56	.53	2.79*
Green	.17	.18	<1.00	.53	.53	<1.00
Mixed	.29	.31	1.10	.73	.71	2.77*

Note. For these analyses, the large number of objects (1,400+) provides high power for the statistical tests. STS = single-target searches for metal threats and IEDs combined; DTS = dual-target search.
* Significantly fewer fixations in dual-target search than single-target search at $p < .05$ after Bonferroni correction.

16) ANOVA. To focus on the dual-target cost, we report only effects and interactions involving the number of targets factor.

The probability of fixating distractors was greater in the combined single-target searches than the dual-target search, $F(1, 657) = 15.92$, $p < .001$, $\eta_p^2 = .024$. This effect was dependent on color: Number of Targets × Color, $F(1, 657) = 3.74$, $p = .01$, $\eta_p^2 = .017$; and on target presence: Number of Targets × Target Presence, $F(1, 657) = 10.46$, $p = .001$, $\eta_p^2 = .016$; with the three-way interaction also being significant: Number of Targets × Color × Target Presence, $F(1, 657) = 2.88$, $p = .04$, $\eta_p^2 = .013$. It should be noted that the size of these effects is very small, but the very large number of distractors contributes power for finding the significant effects.

Post hoc *t* tests (see Table 2) comparing single- and dual-target fixation rates for each color across target-present and target-absent trials showed fewer fixations in dual-target search than single-target search for blue-black, orange, and mixed items on target-absent trials (ts > 2.77, $p < .05$, $r \geq .133$). There were no significant differences between single- and dual-target searches for blue-black, orange, and mixed items on target-present trials (ts < 2.25, $p > .20$) and for green items (ts < 1).

For the strict IA analysis, there was also a significant interaction for Number of Targets × Target Presence × Session in the main ANOVA. In dual-target search, in the last session, *t* tests showed fewer fixations to blue-black items on target-absent trials and a trend toward more fixations to green items on target-present trials, compared with the combined single-target searches. These results therefore mirror those shown for the extended IAs, with evidence for not enough fixations on target-color items and too many on non–target-color items.

In sum, dual-target search resulted in fewer fixations on items that were the same color as the targets (blue-black, orange, mixed) compared with single-target search, whereas there were no differences for items that were not target colored (green). These findings show that the reduction in fixations in dual-target search compared with single-target search did not occur for all colors, but occurred only for target-color items. Given that a similar decrease did not occur for non–target-color items, these results imply that the representation(s) guiding dual-target search are not as effective as in single-target search: Fewer target-color items are fixated, but a similar number of nontarget items are fixated.

There was a trend toward significance for Number of Targets × Target Presence × Session, $F(2.9, 1926.5) = 2.11$, $p = .10$. No other interactions involving number of targets were significant (Fs < 2.00, $p > .11$).

Discussion

The first aim of the experiment was to replicate the dual-target cost in search for metal threats and IEDs in X-ray images, and to determine whether a cost exists if objects are overlapping. As discussed in the introduction, guidance may not be effective in overlapping images because of unreliable object coloring; hence, there may be no cost to including an additional target. Performance in dual-target search was generally worse than in either single-target search, with longer RTs and lower accuracy compared with single-target search for metal threats and with longer RTs compared with single-target search for IEDs. Accuracy was similar across dual-target search and single-IED-search, but for overlapping images, more targets were missed in dual-target search.

Given the blocked design, the target images may become more familiar in single-target search than in dual-target search, but this familiarity cannot be producing the dual-target cost. If it were, there would be a divergence in accuracy between single- and dual-target searches across session, but no interaction was observed between the type of search (single-metal-threats, single-IEDs, dual-target) and session ($p = .405$). In addition, previous research (Menneer et al., 2009) shows a dual-target cost with metal threats and IEDs when the search condition is manipulated within-participant such that each participant received the same exposure to the target images.

In this task, one target is generally more difficult to find than the other, raising the possibility that the dual-target cost simply reflects the extra effort required to find the more difficult target. However, taking accuracy and RT together, there is a dual-target cost relative to both single-target searches; hence, search for both targets exhibits a cost beyond simply being limited by the more difficult target. Consistent with this proposition, previous research with simpler stimuli (e.g., Stroud et al., 2012) has demonstrated a dual-target cost in search accuracy and in color guidance for targets of equal difficulty. Thus, the dual-target cost reflects something more than just the asymmetry in target difficulty alone.

The second aim of this experiment was to examine eye movements to better understand the strategy used in dual-target search. Single- and dual-target search can be compared in two ways. First, dual-target search could be implemented as simultaneous search, in which fixations are the same as those made in single-target search, and each fixated object is compared with both target representations. In this case, the dual-target fixations would be the same as those made in the single-target searches, and the fixation durations would be longer in dual-target search. To test this strategy, our first test compared the probability of fixation and the fixation duration in dual-target search with those in each of the single-target searches separately. The results clearly showed that participants were fixating more objects in dual-target search than in single-target searches, and that fixation durations did not differ across single- and dual-target searches.

On the other hand, it may be so difficult to search for two targets simultaneously that participants perform two sequential single-target searches, one for each target. Under this strategy, the fixations in dual-target search would be the same as the combined fixations over both single-target searches. To test this strategy, we compared the probability of fixation in dual-target search with the combined probability of fixations across both single-target searches. As explained below, the results fall between these two extremes.

First, we compared fixations to given colors in dual-target search with those in separate single-target searches. The majority of eye movements in all searches were made to objects of the same color as the predominant target color(s): blue-black for metal threats and mixed or orange for IEDs. In dual-target search, the number of fixations to blue-black objects was equivalent to that in single-target search for metal threats, and the number of fixations to orange items was equivalent to that in single-target search for IEDs. However, there were more fixations to mixed items in dual-target search than in either single-target search, and most notably more fixations to non–target-color items (green). Overall,

there were more fixations than should have been necessary in a dual-target search that matched the efficiency of the single-target searches, and these extra fixations went to items with nontarget colors.

Second, we compared fixations to given colors in dual-target search with those in both single-target searches combined. There were not as many fixations as would be expected in the dual-target conditions if two separate searches were being conducted serially: The second comparison shows that there were fewer distractors fixated in dual-target search than in the combination of the two single-target searches. These data could be interpreted as reflecting stronger guidance in dual-target search than in single-target searches, which reduces distractor fixations. However, if guidance to targets was stronger in dual-target search, the dual-target cost in accuracy and particularly in the miss rate would not be observed. Rather, this result suggests that participants were not conducting as full a search in dual-target search as they would in two separate single-target searches; they make too few fixations, and the fixations that they make are disproportionately devoted to non–target-color items. These fixation rates suggest a reduction in guidance in the dual-target search, with weaker target representation(s) causing target-color items to be missed. The targets were especially likely to be missed in dual-target search when objects were overlapping.

This finding is in line with previous experiments with search among abstract color–shape conjunctions for two very different colors, which showed a reduction in guidance in dual-target search compared with single-target search (Stroud et al., 2011). In that study, target-color objects were fixated at about the same level across single- and dual-target searches, but more non–target-color objects were fixated in dual-target search than single-target search. The current dual-target cost reflects the same relationships and overall profile across the fixation probabilities, but with an additional reduction of fixations in dual-target search overall. This combination results in fewer fixations to target-colored objects than in single-target search, whereas irrelevant non–target-colored objects are fixated at the same rate. The X-ray stimuli used here are much more complex than the Stroud et al. (2011) simple color–shape conjunctions. The complex X-ray stimuli make search more difficult, and fewer resources are available to monitor and control search. This limited control may lead participants to give up on search early, without giving themselves enough time to be guided to target-color objects.

In Section C, the probability of fixating distractors was combined across the two types of single-target search for comparison with dual-target search. It is worth noting that this comparison does not account for the differences in RT. The combined single-target search will have a longer overall RT than the dual-target search, thereby allowing more time for more fixating distractors. If the combined single-target fixation rates were adjusted to compensate for the extra time spent searching, then those fixation rates would be reduced. This reduction in fixation rates for target-color and non–target-color objects would produce a pattern that would be more similar to that found in Stroud et al. (2011, 2012) with abstract stimuli, namely, more non–target-color distractors fixated in dual-target search than in single-target searches, and no difference between target-color distractors. However, accounting for RT differences would not alter the relationships between target-color and non–target-color fixations: Dual-target search increases the number of non–target-color fixations relative to target-color fixations, which is the key to understanding the guidance cost in dual-target search. In addition, with respect to the application of airport security screening, we believe that the current comparison is more ecologically valid than factoring out RT for the comparison.

Eye-movement measures, by necessity, were examined with nonoverlapping images (768 trials), although the majority of displays that participants experienced comprised overlapping images (no eye tracking, 4,608 trials). Search strategy could be qualitatively different across the two types of display, in that guidance might break down completely with overlapping images. However, the performance data are extremely similar across both types, and we therefore believe that the eye-movement data are informative about the search behavior in general rather than being limited to the nonoverlapping displays. Although overlap and occlusion occur in the non-eye-tracking sessions, there is no evidence for a qualitative shift in strategy or search behavior between the two types of display.

The third aim was to determine whether guidance changes over practice and experience. There is evidence that guidance changed during the course of the experiment, with the number of revisits in dual-target search being greater than in single-target searches in early sessions, but becoming equivalent to single-target searches in later sessions. In addition, when a target was present, the colors were fixated with equal probabilities across single-target searches and dual-target search, particularly in the last session. These results suggest that the target representations in dual-target search were refined and made more effective with practice, allowing better use on target-present trials. However, a cost in guidance remained for dual-target search, with fewer fixations to target-color items and a similar number of fixations to nontarget items, compared with the combined fixations in single-target search.

In conclusion, participants were unable to perform a single simultaneous search for two targets with the same fixations that they made in a single-target search, but they also failed to sequentially search for two targets as thoroughly as they would if they had performed two separate searches. These findings reflect a reduction in color guidance in dual-target search for categorically defined targets that remains even after practice. The current results, along with those of Stroud et al. (2011), show that dual-target search raises the rate of fixations to non–target-color items relative to target-color items, lowering the effectiveness relative to single-target search.

This conclusion has implications for applied search tasks. Threat items are missed in dual-target search (Menneer et al., 2009), with the current study showing that this is particularly the case for overlapping X-ray images, and that the reduction in search guidance is the cause for these misses. The implication for X-ray security screening is that screeners searching for multiple targets may not be as selective in guiding their attention to targets as they are in two separate independent searches, one for metal-threat items and one for IEDs. This and previous research suggest that screeners should specialize in search for metal threats or in search for IEDs in order to narrow their search to similarly colored objects and ignore those objects that are not likely to be either type of target. Such focus allows more target-color objects to be attended such that search is more accurate.

There are multiple types of objects that screeners need to search for, such as water bottles, explosives, guns, scissors, knives, razor

blades, and so forth. We are not suggesting that a different screener be assigned to each type of item. Rather the present results, together with previous dual-target research, show that target objects can be pooled into categories based primarily on color, such that water bottles and explosives are in one category, given that they all generally show up as orange in X-ray images, and all metal threats (guns, knives, razor blades, scissors) are in another category. It may also be possible to group objects by shape, but such a conclusion goes beyond the current data and previous findings that show successful dual-target search when targets are similar in color. With regards to shape, the classification of a stimulus as a target or a distractor is faster for two similarly shaped targets than for two dissimilar targets (e.g., Dykes & Pascal, 1981), which gives some evidence that search targets could be grouped by shape. For X-ray images of complex objects, however, shapes are less well defined, and can vary greatly within object category because of viewpoint and because of malleability of the material (e.g., explosives in IEDs). Therefore, in this applied task, we would argue that color provides a more reliable cue to object identity than shape, despite changes to color when objects overlap.

The recommendation for specialized screeners can be implemented in two ways, depending on the specification requirements of the security situation and the volume of passengers. First, in quieter times, two screeners from two separate baggage scanners could be relocated centrally, with each seeing the images from both scanners and specializing in one type of threat. Second, in times of high security alert, a second screener could be recruited at the baggage scanner to allow specialized search to be conducted. Using the data from the final non-eye-tracking session, which represent conditions that are most similar to those experienced by security screeners (i.e., overlapping images and well-practiced), we estimate that this second screener would not only reduce the number of missed targets by 28%, he/she would also increase the speed of passengers passing through the security checkpoint by 68%. Therefore, the addition of a second screener would not double the cost because passenger throughput would be increased relative to having a single dual-target screener. An alternative to specialization is to train screeners to conduct two separate single-target searches of the same display. This approach has the risk that the second search may suffer because of familiarity or fatigue from the first pass of the display. However, other research has demonstrated that, under instruction, participants are able to conduct dual-target search either simultaneously or sequentially (Beck, Hollingworth, & Luck, 2012). Another possible avenue is that some screeners could be tasked with multiple low-difficulty target objects while others specialize in the more difficult objects.

Although this research is aimed at the airport security application via the stimuli used, the current results also apply to any situation in which searchers are searching for multiple different targets, for example, air traffic control, or searching for multiple likely causes of pain in a medical image.

The results not only give evidence for the source of the dual-target cost, but also reveal many errors in IED search compared with metal threats. When searching for IEDs, participants tended to respond inaccurately and seemed to give up on search by responding quickly when images were overlapping (e.g., Chun & Wolfe, 1996). There are two main reasons why search for IEDs could be more difficult than search for metal threats. First, IEDs typically have a less predictable shape than metal-threats. Second, the orange explosive of an IED is less dense than metal, so it is more likely to be masked by overlapping objects than the atomically dense metal threats. The color changes resulting from overlap reduce the efficacy of the target representation used to guide search because search for "orange explosive" is less helpful in identifying target IEDs when the color is overlaid with blue or green images. In some instances, the characteristic combination of wires and explosives may even be occluded by other denser objects. This occlusion is less likely to occur with metal threats because they are dense metal objects themselves, and therefore tend to be visible through most other distractor objects. Such color changes or occlusion may lead participants to believe that if they cannot find the IED reasonably quickly, they will not find it at all, and that they cannot complete the task accurately. Future work will examine whether practice with searching X-ray images in 3D will allow searchers to develop a better understanding of object colors and their combinations, which could improve X-ray image interpretation and search guidance.

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