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Dual Target Search: Attention Tuned to Relative Features, Both Within and Across Feature Dimensions

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Current models of attention propose that we can tune attention in a top-down controlled manner to a *specific feature value* (e.g., shape, color) to find specific items (e.g., a red car; *feature-specific search*). However, subsequent research has shown that attention is often tuned in a context-dependent manner to the *relative features* that distinguish a sought-after target from other surrounding nontarget items (e.g., larger, bluer, and faster; *relational search*). Currently, it is unknown whether search will be feature-specific or relational in search for multiple targets with different attributes. In the present study, observers had to search for 2 targets that differed either across 2 stimulus dimensions (color, motion; Experiment 1) or within the same stimulus dimension (color; Experiment 2: orange/redder or aqua/bluer). We distinguished between feature-specific and relational search by measuring eye movements to different types of irrelevant distractors (e.g., relatively matching vs. feature-matching). The results showed that attention was biased to the 2 relative features of the targets, both across different feature dimensions (i.e., motion and color) and within a single dimension (i.e., 2 colors; bluer and redder). The results were not due to automatic intertrial effects (dimension weighting or feature priming), and we found only small effects for valid precueing of the target feature, indicating that relational search for two targets was conducted with relative ease. This is the first demonstration that attention is top-down biased to the relative target features in dual target search, which shows that the relational account generalizes to multiple target search.

Public Significance Statement

In the quest to successfully navigate an overwhelmingly abundant visual world we have honed the ability to select only the behaviorally relevant visual input. Still, in search for a certain item, other irrelevant items can "capture" attention and distract us. While current theories of attention predict that only target-similar items can attract attention, the present study shows that all attributes that match the relative features of sought-after target items (e.g., redder) can attract attention and the gaze. This suggest that attention is *by default* tuned to relative features, even in search for 2 possible target attributes. This dramatically increases the number of items that can attract attention and the gaze and distract us from an ongoing task, but may convey benefits in natural environments where the specific feature values of objects typically vary.

Keywords: attention, visual search, gaze, capture, relational

During every waking moment, the visual world presents far more information—objects, lights, and movement—than we could hope to process. To cope with these limitations, the visual system has evolved mechanisms to attend only to potentially relevant objects. Top-down control mechanisms of attention allow limiting selection to stimuli that match our behavioral goals. For instance, when looking for a red car, attention is top-down tuned or biased to red, so that only red stimuli can attract our attention (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Wolfe, 1994). In addition, salient stimuli can attract attention in a bottom-up, stimulus-driven manner, independent of, or even in opposition to our top-down goals (e.g., Joseph & Optican, 1996; Theeuwes, 1991, 1992; Jonides & Yantis, 1988). Yet, previous research suggests that even involuntary, reflexive shifts of attention and the gaze (*attentional capture* and *gaze capture*) are more strongly driven by top-down processes, as involuntary selection of target-similar items is more frequent than of salient, target-dissimilar items (e.g., Becker, 2018; Eimer & Kiss, 2008; Folk & Remington, 1998; Ludwig & Gilchrist, 2002).

For instance, in an eye movement study, Ludwig and Gilchrist (2002) asked observers to search for a green target among three other gray nontarget items, and to ignore an irrelevant distractor,

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which could have the same color as the target or the nontargets (target-similar vs. dissimilar), and that could be presented with or without a sudden onset that rendered it salient versus nonsalient (i.e., by showing the distractor in a previously occupied or empty location). The results of their study showed that target-similar distractors attracted the gaze most strongly, both when they were presented with a salient onset and without a salient onset. The salient target-similar distractor was also selected slightly more frequently than the nonsalient target-similar distractor, but these differences were rather small, indicating that bottom-up saliency does not strongly drive attention or eye movements (Ludwig & Gilchrist, 2002; see also Becker, 2018).

The finding that an irrelevant distractor can attract attention more strongly when it is similar to the target is an instance of top-down contingent attentional capture (Folk & Remington, 1998; Folk et al., 1992). It has also often been interpreted as evidence for *feature-specific tuning of attention* (e.g., Duncan & Humphreys, 1989; Martinez-Trujillo & Treue, 2004). According to the currently most prominent models of attention, attention is usually *tuned* or *biased* to the target feature value even before the target appears (e.g., red, green), which increases the attention-driving capacity of all items that have this feature (e.g., Duncan & Humphreys, 1989; Navalpakkam & Itti, 2006; Wolfe, 1994).

Contrary to this prediction of a *similarity effect*, subsequent studies found that target-dissimilar distractors can still strongly attract attention and the gaze, provided that they have the same *relative feature* as the target (e.g., redder, larger, or darker). These results have been taken as evidence for a *relational account* of attention (Becker, 2010a), which centrally proposes that attention is often tuned to the relative feature of the target rather than the target's specific feature value—that is, the feature that the target has in relation to other items in the search context (e.g., redder, larger, and darker). For instance, when observers are searching for an orange target among yellow nontargets (*redder target*), and the target is usually (≥50% of all trials) the reddest item in the visual field, it can be found by tuning attention to all redder items, or the reddest item. The hallmark of such a relational search strategy is that all distractors that are *redder* than the other items (e.g., red-orange or red) can strongly attract attention and the gaze—even when they are very dissimilar to the target and could not be confused with the target (e.g., Becker, 2010a; Becker, Folk, & Remington, 2010, 2013; Becker, Harris, Venini, & Retell, 2014). Moreover, in visual search, all distractors that are redder than the target itself (e.g., red-orange, red) will attract attention and the gaze more strongly than a target-similar distractor with the same color as the target (orange; e.g., Becker, Harris, et al., 2014; Martin & Becker, 2018; York & Becker, 2020). When the orange target is presented among red nontarget items in a different block (yellower target), yellow-orange and yellow distractors attract attention and the gaze more strongly than target-similar orange distractors, showing that attention has now been tuned to yellower, or the yellowest item in the visual field (Becker, 2010a; Becker, Harris, et al., 2014).

The finding of stronger capture by redder or yellower items is also consistent with broad top-down tuning to a color category (e.g., red; *Guided Search 2.0*; Wolfe, 1994), or tuning attention to a shifted, exaggerated target feature value, as proposed in *optimal tuning accounts* (e.g., Navalpakkam & Itti, 2007; Scolari & Serences, 2009). However, multiple studies showed that attention is indeed genuinely tuned to the relative target feature in a context-dependent manner, not to a broadly defined feature category (Becker, 2010a; Becker, Valuch, & Ansorge, 2014; Becker, Folk, & Remington, 2013), or to a feature that is shifted away from the nontarget feature to a more extreme feature value (e.g., Becker et al., 2013; York & Becker, 2020). For instance, in a variant of the spatial cueing paradigm, Becker et al. (2013) showed that relatively matching distractors can attract attention even when they have the same color as the *nontargets*, which is inconsistent with broad categorical tuning or optimal tuning (see Becker, Harris, York, & Choi, 2017 for similar findings in conjunction cues and targets). Moreover, in a visual search task, York and Becker (2020) showed that distractors can still attract attention and the gaze when they are very dissimilar from the target and outside the area of optimal tuning. Collectively, these results show that attention is genuinely tuned to the relative feature of the target, and suggest that previous results attributed to broad categorical or optimal tuning were in fact because of relational tuning (e.g., Becker, 2010a, 2013a, 2013b; Becker et al., 2013).

Thus, rather than tuning attention narrowly to a specific feature value or broadly to a category, the visual system exploits *how* a sought-after item differs from the context of irrelevant items, and tunes attention to these relative features (e.g., redder). For instance, when tuning attention to all redder items, attention is first drawn to the reddest item, then the next reddest item, and so forth, which can be formally described by a vector account (e.g., Becker, 2010a, 2013b). In natural environments and in everyday life, it is usually known how a sought-after item will differ from the context of irrelevant items, so that relational search does not pose any limitations on visual search. Experiments that presented new, unknown images have moreover shown that we can quickly extract statistical information about the features present in a scene (e.g., feature averaging effect; e.g., Chong & Treisman, 2003), so that relational search may even be possible with new, unknown images (though this would still need to be confirmed empirically).

Once attention is tuned to the relative target feature, attentional capture is largely independent of the featural similarity to the target and depends only on whether an item matches the relative feature of the target. This results in a larger number of items that can potentially produce distraction. In the natural environment, tuning attention to the relative feature may still confer benefits, because the exact feature value of items varies (e.g., due to differences in the lighting conditions, or changes in perspective or distance to objects), whereas the relative features of objects are relatively constant and, thus, allow locating a sought-after object in a wider range of conditions. In line with this possibility, subsequent studies established that top-down tuning to the relative target feature generalizes to other dimensions to guide attention in search for luminance, size, and shape (e.g., Becker, 2010a, 2013a, 2013b), and even in search for conjunction stimuli (Becker, Atalla, & Folk, 2020; Becker, Harris, et al., 2017).

Subsequent studies showed that attention can also be tuned to the exact feature value of the target (e.g., Becker, Harris, et al., 2014; Harris, Remington, & Becker, 2013; Schönhammer, Grubert, Kerzel, & Becker, 2016). However, this feature-specific search mode is only used when the target cannot be found by its relative features. For instance, when an orange target is embedded among randomly varying nontargets that can be either all red or all yellow, attention is tuned to orange, resulting in the strongest capture by orange distractors (Harris et al., 2013; Schönhammer et al., 2016). These findings show that we can tune attention to a particular feature value, but this is only observed if the conditions do not allow relational search.

Collectively, previous studies show a preference for a relational search over feature-specific search, across multiple different target features and dimensions (e.g., color, shape, luminance, and size; Becker, 2010a, 2013a, 2013b; Schönhammer, Grubert, Kerzel, & Becker, 2016), and also in conjunction search tasks (e.g., Becker, Harris, et al., 2017, 2020).

However, the current evidence for relational top-down tuning is still limited, as previous studies only tested single target searches, in which the target always had the same feature. Hence, it is currently unclear whether relational tuning is preferred, or even possible, when the target feature varies randomly and would require tuning attention to multiple features.

Dual Target Search

It has been suggested that real-world search often requires dual target search; that is, searching for a target that can have various different features (e.g., Grubert & Eimer, 2015, 2016; Wolfe, 1998). Accordingly, several studies have examined whether we can efficiently search for two different targets that can vary across feature dimensions (e.g., color and motion; Kumada, 1999; see also Grubert & Eimer, 2015; Treisman & Gelade, 1980), across spatial locations (Adamo, Pun, Pratt, & Ferber, 2008), or different targets within a single feature dimension (e.g., color: red and green; Harris, Becker, & Remington, 2015). The results so far suggest that we can tune attention to multiple features, either by tuning to two or more items across different feature dimensions in parallel (i.e., color and orientation, Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; color, shape, size; Adamo et al., 2008; Quinlan & Humphreys, 1987), or by rapidly switching between different features (e.g., Lien, Ruthruff, & Johnston, 2010; Lien, Ruthruff, & Naylor, 2014).

However, tuning attention to two target features may come at a cost, compared with two, temporally separated single-target searches, as reflected in poorer accuracy (i.e., Menneer, Cave, & Donnelly, 2009, but see also Biderman, Biderman, Zivony, & Lamy, 2017; Dombrowe, Donk, & Olivers, 2011; Houtkamp & Roelfsema, 2009; Menneer et al., 2007; Stroud, Menneer, Cave, & Donnelly, 2012), and greater susceptibility to distraction (Menneer et al., 2009; Moore & Weissman, 2010; Stroud et al., 2012; see also Kumada, 1999; Roper & Vecera, 2012). This *dual target cost* also seems to be greater for multiple-target search within a single target dimension than for multiple target search across feature dimensions (Menneer et al., 2007; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; but see Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2016; Moore & Weissman, 2010), which suggests that dual target search within one dimension can lead to additional conflicts or competition (e.g., Treisman & Sato, 1990).

In search for different targets within a stimulus dimension (e.g., different colors), observers can also engage in a *singleton search mode* (Bacon & Egeth, 1994), in which all salient items can potentially attract attention (Folk & Anderson, 2010; Harris et al., 2015; but see Becker, Martin, & Hamblin-Frohman, 2019). In this singleton search mode, attention seems to be tuned rather broadly to all singletons or all salient items within the target dimension (e.g., color; Harris et al., 2015). For example, in search for a red or green target among gray nontargets, a blue cue can attract attention to the same extent as a red or green cue, even though the target is never blue (Folk & Anderson, 2010; Harris et al., 2015).

However, singleton search does not seem to be the default search strategy when the target feature can vary: Becker et al. (2019) found weaker capture by blue than red or green, which indicates that attention may also be tuned more specifically to the target colors. Moreover, several studies found that attention can be tuned to two possible target colors (e.g., red and green) so that only these colors attract attention, when other equally salient colors are occasionally presented as nontarget items (e.g., a blue cue would not capture if blue is a property of the nontarget items; Grubert & Eimer, 2016; Irons, Folk, & Remington, 2012). These findings were obtained with behavioral measures as well as with electrophysiological measures (e.g., the N2pc in the electroencephalogram (EEG) of participants; Grubert & Eimer, 2016), and show that attention can be tuned more narrowly to different features, without engaging in singleton search (Bacon & Egeth, 1994).

However, these previous studies did not distinguish between feature-specific search or relational search, as the target-matching colors always also matched the relative feature of the target, and target-mismatching colors always mismatched the relative target feature (Adamo et al., 2008; Becker, Lewis, & Axtens, 2017; Grubert & Eimer, 2016). Thus, as these previous studies only ruled out singleton search as an alternative explanation, it is still an open question whether attention is usually biased to the specific feature values of the possible targets in dual search tasks, or their relative features.

The Current Study

The aim of the current study was to test how attention is top-down tuned to two possible target features, both across two separate feature dimensions (motion, color; Experiment 1) and within the same feature dimension of color (when the two targets have two different colors; Experiment 2). To test this question, we tracked the eye movements of observers in a visual search paradigm with an irrelevant salient onset distractor, which has been used extensively in previous studies to investigate how attention is top-down tuned to the target (e.g., Becker, Lewis, & Axtens, 2017; Born, Kerzel, & Theeuwes, 2011; Mulckhuyse, Van Zoest, & Theeuwes, 2008).

As in previous studies, we used different types of distractors that either matched the target feature value (e.g., orange) or only the relative target feature (e.g., redder), to ascertain whether attention was tuned to the target feature values or the target's relative features. In addition, we included another salient distractor with an unrelated color (e.g., yellow) to distinguish these search strategies from a singleton search mode, in which all salient items can attract attention (e.g., Bacon & Egeth, 1994; Folk & Anderson, 2010; Harris et al., 2015).

To ensure that the observed distractor effects can be attributed to top-down search strategies, we had to rule out *feature priming* or *priming of pop-out effects*: Previous studies showed that attention is automatically biased (*primed*) to select the target that was presented on the previous trial, which facilitates selection on repeat trials compared with switch trials (Maljkovic & Nakayama, 1994; see also Found & Müller, 1996). This *priming effect* has been attributed to an automatic carry-over effect that operates largely outside of top-down control (e.g., Awh, Belopolsky, & Theeuwes, 2012; Pinto, Olivers, & Theeuwes, 2005; Theeuwes, 2013; Theeuwes, Reimann, & Mortier, 2006; but see Becker, 2007; Fecteau, 2007; Folk & Remington, 2008; Wolfe, Butcher, Lee, & Hyle, 2003). To ascertain that our effects were indeed caused by top-down tuning rather than automatic priming effects, we assessed the priming effect (i.e., difference between repeat vs. switch trials), and focused the main analyses on (unprimed) switch trials.

To assess capture by the different distractors, we centrally monitored the eye movements of all observers during visual search. As eye movements are usually preceded by a covert shift of attention to the saccade target location (Deubel & Schneider, 1996), measuring the proportion of first eye movements to each distractor allows us to index how attention was allocated to the search items (e.g., Becker, 2010a; Zelinsky & Sheinberg, 1997).

As it is possible to covertly select the distractor without a concomitant eye movement (e.g., Findlay, 1997), we also measured the target saccade latencies in each distractor condition—that is, the time from the onset of the search display to selection of the target. If attention is covertly shifted to the distractor without a concomitant eye movement, this should delay selection of the target, which would be reflected in elongated target saccade latencies in a subset of distractor conditions (e.g., Becker, 2010a; Becker, Lewis, & Axtens, 2017; Deubel & Schneider, 1996; Findlay, 1997; Ludwig & Gilchrist, 2002). Based on previous studies with this paradigm, we expected either no differences or only small latency effects, showing that those distractors that attract the gaze most strongly also delay the first eye movement to the target (e.g., Becker, 2018; Becker, Lewis, & Axtens, 2017; York & Becker, 2020).

Experiment 1: Two-Target Search Across Feature Dimensions

To test whether top-down tuning to multiple target features is based on tuning to two specific target-defining feature values (*similarity-based guidance*), or to the relative target feature (*relational guidance*), we asked observers in Experiment 1 to search for a singleton target defined in one of two feature dimensions, *color*, or *motion*. In different displays, the target could differ either in motion or color from the nontarget items, and within each display, the target was always presented among the same set of nontargets. Specifically, on color target trials, the target was a greenish blue *aqua* (greenish blue) square that was presented among turquoise (more green) nontargets (i.e., bluer target condition). On motion target trials, all search items were gray and rotated, whereby the target rotated slightly faster (medium-fast rotating target) than the nontargets (which were rotating slowly). Hence, the target could be located either by tuning attention to the specific feature values of the target items (aqua, fast rotation) or by tuning attention to its relative features (bluer/bluest item, faster/fastest rotation).

The irrelevant distractor was rendered salient by presenting it with a sudden onset. That is, before the search display we presented uniform gray premasks disks at the target and nontarget locations, and presented the onset distractor in a previously empty location (see Figure 1 for an illustration). Participants were instructed to ignore the onset distractor, as it was irrelevant to the task.

In the color target condition, the target was an aqua (greenish blue) square among turquoise (more green) nontargets, so the target was always bluer than the nontargets. The distractor could appear in one out of four colors; the same color as the target (*target-similar*), as the nontargets (*nontarget-similar*), it could be blue and thus, match the

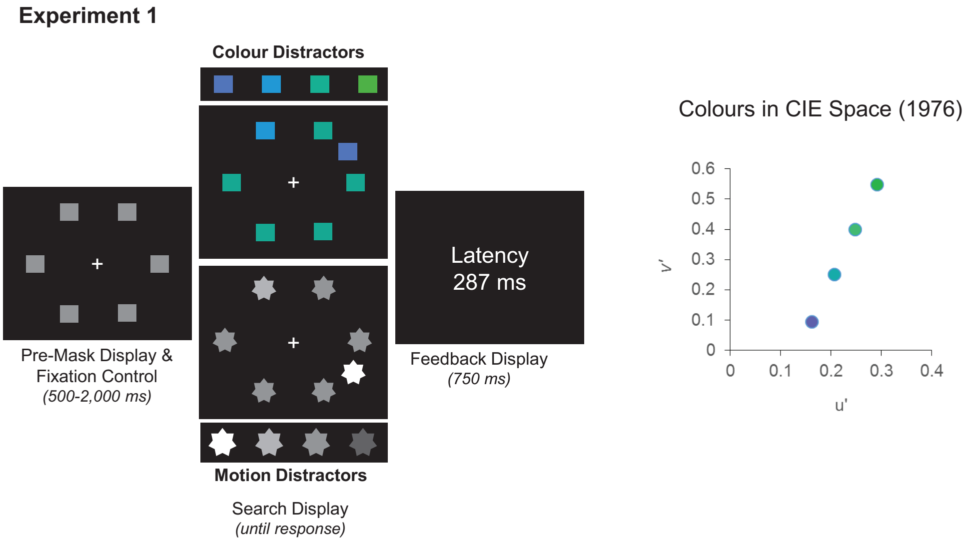

Figure 1. The left panel shows the stimulus conditions and procedure of Experiment 1. Observers had to search for an aqua target (top) or a medium-fast rotating motion target (bottom, with different motion speeds displayed as different gray values; lighter = faster rotating) while ignoring an irrelevant onset distractor that could have any of the features listed above and below the target displays. After each trial, a feedback display showed the latency of the first eye movement. The right panel shows the position of the colors in CIE (1976) space. See the online article for the color version of this figure.

relative color of the target (*relatively matching*) or it could be green and thus, differ in the opposite direction from the nontargets as the relatively matching color (*opposite distractor*).

In the motion target condition, all items were rotating (anticlockwise), with the target rotating at a higher speed than the nontargets (relatively faster target). The four irrelevant distractors could rotate either at the same speed as the target (target-similar) or the nontargets (nontarget-similar), rotate faster than the target item (relatively matching), or slower than the nontargets (opposite).

According to a feature similarity account, attention should be tuned to the specific feature values of the targets (i.e., aqua and fast rotation), which should lead to the strongest capture by the two target-similar distractors and declining capture rates for less similar distractors (including relatively matching distractors). A corresponding similarity effect would provide strong evidence for a feature-specific search strategy. According to the relational account, attention should be tuned to the relative feature of the target (i.e., bluer/faster), so that the bluest/fastest items in the display attract attention most strongly. As a consequence, the relatively matching distractors should attract attention most strongly, followed by target-similar distractors. A corresponding result would be the hallmark of relational search, and indicate that attention was tuned to the relative features of the two targets (e.g., Becker, 2010a; Becker, Harris, et al., 2014). A third possible outcome is that we will find equal capture by all salient distractors, which would indicate that attention was not tuned to the target features (neither to the specific feature value nor relationally), but instead engaged in a singleton search mode (Bacon & Egeth, 1994).

To index selectivity, we centrally measured capture by the distractor, as indexed by the proportion of first eye movements to each of the different distractors (e.g., Becker, Harris, et al., 2014; Mulckhuyse et al., 2008). Moreover, we controlled for covert attentional selection of distractors by measuring the target fixation latencies separately for each distractor condition.

As mentioned above, we excluded repeat trials for a part of the analysis, to rule out that the results were due to automatic intertrial priming effects rather than top-down tuning effects. However, as most previous studies found that priming merely contributed to selectivity without fully accounting for it (e.g., Becker, Ansorge, & Horstmann, 2009; Folk & Remington, 2008; Kristjánsson, Wang, & Nakayama, 2002; Leonard & Egeth, 2008), we did not expect large differences in selection between repeat and switch trials. Rather, based on previous studies, we assumed that priming would have rather moderate effects on selection, so that differences between distractors would be mainly caused by top-down tuning of attention, which should be evident both on repeat trials and switch trials.

Method

Participants. The sample size for the present experiment ($N = 23$) was the same as in a previous experiment that used very similar methods and procedures (York & Becker, 2020; Experiment 1). In the earlier study, the predicted relational effect of more frequent selection of a relationally matching (blue) than target-similar (aqua) distractor with a single color target (aqua) was detected with a mean difference value of 10.8% ($SD = 16.0$; $\eta_p^2 = .341$). Computing the required sample size to detect a corresponding effect ($dz = 0.675$) at an alpha level of .05 and a power of 0.9 with one-tailed testing in G*Power yielded a required sample size of 21 participants.

The 23 participants of Experiment 1 (10 men, mean age: 21.7) all reported normal or corrected-to-normal vision. Participation was voluntary and participants were compensated with $10AU/hr for their time. All materials and procedures used in Experiments 1 and 2 were in line with the Declaration of Helsinki, and approved by the Human Ethics Committee of The University of Queensland.

Apparatus. A Dell Optiplex 745 computer (Dell, Round Rock, TX) and a Samsung SyncMaster 967DF CRT color monitor were used for the experiment. All stimuli were presented on a monitor with a resolution of 1280 × 1024 pixels and a refresh rate of 85 Hz. A video-based eye tracker (Eyelink 1000, SR Research, Ontario, Canada) recorded eye-movements with a spatial resolution of 0.1° and a temporal resolution of 500 Hz. A standard mouse was used to record responses. Observers viewed the screen from a distance of 62 cm, with their heads fixated by the forehead and chinrest of the eye-tracker. Presentation software (Neurobehavioral Systems) controlled the sequence of trials in the experiment and provided performance feedback during the experiment.

Stimuli. All stimuli were presented against a black background. The fixation display consisted of a white cross (size: 0.27° × 0.27°) presented at the center of the screen. The premask display consisted of the fixation cross and 6 gray squares (size: 1.48° × 1.48°) that were distributed evenly on the outlines of an imaginary circle with a diameter of 15.7° (see Figure 1).

On color target trials, one of the gray premasks changed to the target color (aqua), whereas the nontarget squares changed to turquoise. On motion target trials, one of the gray premasks was set to fast rotating motion, whereas the nontarget squares were slower rotating. The onset distractor was a colored square, or rotating item (for color and motion target trials, respectively) that appeared in a previously empty location between two nontarget items, though never directly adjacent to the target.

On color target trials, the onset distractor could have one out of four different colors: blue (relationally matching), aqua (target-matching), turquoise (nontarget-matching), or green (opposite). The colors were matched for luminance with a CRS ColorCal MKII colorimeter, and had the following luminance and CIE (1976) color values: blue, L*u'v'*: 13.64, 0.162, 0.095; aqua, L*u'v'*: 13.95, 0.207, 0.25; turquoise, L*u'v'*: 13.73, 0.248, 0.399; green, L*u'v'*: 12.76, 0.291, 0.547.

On motion target trials, the onset distractor could have one out of four different rotational speeds: very fast (relationally matching), medium-fast (target-matching), medium-slow (nontarget-matching), or very slow (opposite). The appearance of different motion speeds was created by the presentation of a square that was rotated by 8.0, 6.6, 3.8, or 2.0°, in an anticlockwise direction, for the fast, medium-fast, slower and slow rotating squares, respectively.[1]

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[1] We did not reverse the mapping of for target and nontarget features, as a pilot experiment showed that reversing the mapping of motion resulted in less efficient, serial search—probably because the fast rotating nontargets produced too much noise to allow immediate detection of the more slowly rotating target. With respect to the color target conditions, previous studies have shown relational search in both directions in visual search (bluer/greener: Martin & Becker, 2018; York & Becker, 2020; redder/yellower: Becker, 2010a; Becker, Grubert, & Dux, 2014), as well as in the spatial cueing paradigm (e.g., Becker et al., 2010, 2013; also with EEG; e.g., Schönhammer et al., 2016).

Design. The design was a 2 (target dimension: color, motion) × 4 (distractor type: relatively matching, target-similar, nontarget-similar, opposite) within-subjects design. The target dimension and type of distractor varied randomly within a block, with the provision that both targets and all distractors were presented an equal number of times. On color target trials, the four possible distractors were blue (relatively matching), aqua (target-similar), turquoise (nontarget-similar), or green (opposite). On motion target trials, the corresponding distractors were rotating very fast (relatively matching), at the same speed as the target (target-similar), at the same speed as the nontargets (nontarget-similar), or slower than the nontargets (opposite). The target and distractor positions were chosen randomly on each trial, with the limitation that the distractor was never presented on a directly adjacent position to the target (see Mulckhuyse et al., 2008 and Becker & Lewis, 2015, for a similar design). The experiment consisted of 768 trials in total, 96 for each distractor type in each of the color and motion target conditions.

Procedure. Participants were instructed to make a fast and precise eye-movement to the target (either an aqua disk or fast rotating item), and to press a mouse-button while they were still fixating on the target, to indicate that they had found the target. Participants were also fully informed of the possible distractors in advance, and told to ignore them as much as possible.

To ensure accurate eye tracking, participants were calibrated with a 9-point calibration at the beginning of the experiment and after each break. Each trial started with the presentation of the premask display which was yoked to a fixation control: The target display was only presented when participants had maintained fixation on the fixation cross (within an area of 50 pixels, i.e., 1.22°) in the premask display for at least 500 ms, plus a random period between 1 and 200 ms (for a maximum of 2,000 ms); otherwise participants were calibrated anew. Immediately after the fixation period, the search display was presented (together with the onset distractor), and remained visible until the observer's manual response. Immediately after the response, participants received written feedback detailing their saccade latency (measured from the onset of the target to the point in time that the gaze had moved about half the distance to the search stimuli (150 pixels or 3.65° from the center of the screen). The feedback display was presented for 750 ms, followed by a 250 ms blank screen. If observers took 500 ms or longer to initiate the first eye movement, the words '*Too Slow*' were additionally displayed below the saccade latency feedback, to discourage participants from delaying their eye movements (e.g., to search covertly for the target). Participants were given regular breaks every 64 trials, and the experiment took about an hour to complete.

Results

Data. Eye-movements were parsed into saccades, fixations, and blinks, using the standard parser configuration of the Eyelink software, which classifies an eye-movement as a saccade when it exceeds a velocity of 30°/s or an acceleration of 8000°/s The first eye movement on a trial was attributed to a target, distractor, or nontarget when it was within 2.77° (200 pixels) of the center of the stimulus (see Becker, 2010a; Becker, Harris, et al., 2014; Becker, Valuch, & Ansorge, 2014, for a similar procedure). Saccade latencies were computed from the onset of the search display to the point in time when the saccade started, according to the velocity and acceleration criteria. Three participants were excluded because they failed to select the target in a subset of conditions (thus, providing no target fixation latencies). Trials in which the first saccade could not be attributed to a stimulus or trials with first saccade latencies below 50 ms or above 1,000 ms were excluded from all analyses, which led to a loss of 9.1% of the data (8.2% because the first eye movement could not be assigned to a stimulus).

The majority of first eye-movements were directed to either the target or the distractor (96.2% of first saccades in color search; 78.4% in search for the motion target). The proportion of first distractor fixations and the target fixation latencies were analyzed with within-subjects analysis of variances (ANOVAs) and two-tailed *t* tests. Where appropriate, we reported the Greenhouse-Geisser corrected *p* values (with the uncorrected *dfs*, for better readability).

Proportion of first distractor fixations. A 2 (target repetition: target repeated vs. nonrepeated) × 2 (target dimension: color, motion) × 4 (distractor type: relatively matching, target-similar, nontarget-similar, opposite) within-subjects ANOVA revealed no main effect of target repetition, $F < 1$, but significant main effects of target dimension, $F(1, 19) = 12.12$, $p = .002$, $\eta_p^2 = .39$, and distractor type, $F(3, 57) = 58.15$, $p < .001$, $\eta_p^2 = .75$. All two-way interactions were significant; target dimension × repetition, $F(1, 19) = 9.77$, $p = .006$, $\eta_p^2 = .34$; Repetition × Distractor type, $F(3, 57) = 4.84$, $p = .009$, $\eta^2{}_p = .20$; Target Dimension × Distractor type, $F(3, 57) = 13.29$, $p < .001$, $\eta_p^2 = .41$, whereas the three-way interaction was nonsignificant, $F < 1$. As shown in Figure 2, the distractor selection rates were higher on switch trials than on repeat trials. To ensure that the observed effects were due to top-down tuning of attention, we formally compared the distractor effects in the different target conditions only on switch trials (with the observed effects being stronger on repeat trials; probably because of priming).

In the color target condition, the relatively matching blue distractor showed the highest selection rates, reflecting that it was significantly more frequently selected than any of the other distractors, including the target-similar distractor, all $ts > 4.2$, all $ps < .001$; $\eta_p^2 = .48–.69$. The target-similar aqua distractor was selected significantly more frequently than the nontarget-similar turquoise distractor and opposite green distractor, both $ts > 4.1$, $ps \leq .001$, $\eta_p^2 = .48–.62$, whereas the selection rates of the nontarget-similar and opposite distractors did not differ significantly, $t(19) = 1.21$, $p = .24$, $\eta_p^2 = .08$.

The motion target trials showed very similar results, with the highest selection rates for the relatively matching (very fast rotating) distractor, which was selected significantly more frequently than all other distractors, all $ts > 2.4$, $ps \leq .024$, $\eta_p^2 = .24–.63$. The target-similar distractor was also selected more frequently than the nontarget-similar and opposite distractor, both $ts > 3.0$, $ps \leq .006$, $\eta_p^2 = .33–.53$, whereas the nontarget-similar and opposite distractors did not differ, $t < 1$, $p = .53$, $\eta_p^2 = .02$. Taken together, the finding of stronger capture by the relatively matching distractor supports a relational account over a feature similarity account, indicating that attention was tuned to the relative features of the target even in dual target search.

Target fixation latencies. To examine whether observers may have covertly selected the distractor in one of the conditions, and

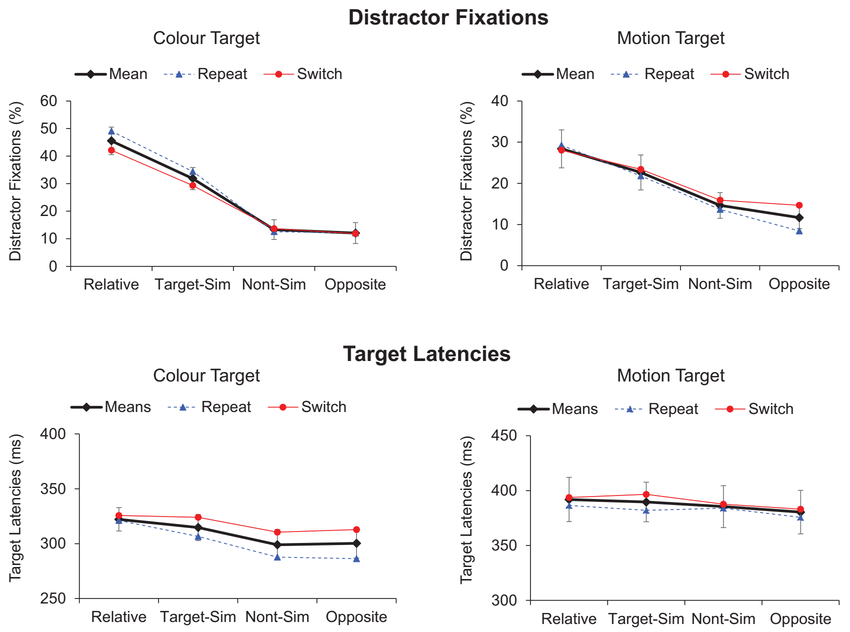

Figure 2. Results of Experiment 1: Distractor fixations (top panels) and target latencies (bottom panels) for the color target (left panels) and the motion target (right panels), depicted separately for the different distractor types and repeat trials versus switch trials. In line with the relational account, a relatively matching distractor attracted the gaze most strongly, significantly more strongly than a target-similar distractor. Repeating the target did not strongly modulate distractor fixations or target latencies. Error bars reflect ±1 *SEM*. See the online article for the color version of this figure.

delayed the first eye movement to the target, we analyzed the mean target fixation latencies with the same 2 × 2 × 4 ANOVA. The results showed a main effect of target repetition, $F(1, 19) = 10.0$, $p = .005$, $\eta_p^2 = .36$, target dimension, $F(1, 19) = 65.60$, $p < .001$, $\eta_p^2 = .79$, and distractor type, $F(3, 57) = 6.60$, $p = .008$, $\eta_p^2 = .27$. None of the interactions were significant, all Fs < 2.0, ps $> .15$. As shown in Figure 2, the target latencies showed a similar result pattern as overt fixations on the distractor, with the longest latencies recorded in the presence of a relatively matching distractor and target-similar distractor, and shorter latencies for nontarget-similar and opposite distractors, across both target dimensions.

In the color target condition, the relatively matching distractor incurred the longest delay for target selection, which was significantly larger than the delays caused by any of the other distractors, all ts > 2.1, ps $\leq .043$, $\eta_p^2 = .21$–$.46$. The target-matching distractor also produced a longer delay than the nontarget-similar and opposite distractor, both ts > 3.7, ps $\leq .001$, $\eta_p^2 = .42$–$.44$; whereas the target latencies of the latter two did not differ from each other, $t < 1$.

The target latencies for the motion target showed the same numerical trends but did not differ significantly between the different distractors, all ts < 1.5, ps $> .16$—probably because of the higher variance in search for the motion target (mean *SEM*: 19.2, compared with 12.4 for the color target; reflecting that the motion stimuli were visually noisier than the color targets). Overall, these results show that the distractors that attracted the gaze most strongly also delayed the first eye movements to the target most. Hence, the data show no evidence for a speed–accuracy trade-off, or for a dissociation between covert selection and overt selection of the distractors.

Time-course of relational tuning. To assess whether participants continuously used relational search to select the two targets, or if the ability to search relationally was acquired only later during the experiment, we inspected distractor fixations across eight different trial bins (96 trials each; 12 trials per distractor and target condition), according to the sequence of trials in the experiment. As shown in Figure 3, the data in the first bin already showed that the relatively matching (blue and fast) distractors attracted the gaze just as strongly or more strongly as the target-matching (aqua and medium-fast rotating) distractors, which is a hallmark of relational search.[2]

Correspondingly, a 2 × 4 ANOVA comparing distractor fixations in the first versus last bin in the bluer target condition revealed only a significant main effect of distractor, $F(3, 57) = 42.4$, $p < .001$, $\eta_p^2 = .69$, but no effect of bin, $F(1, 19) = 3.0$, $p = .096$, and no significant interaction, $F < 1$. The same analysis performed over the motion target condition showed a significant main effect of bin, $F(1, 19) = 12.1$, $p = .003$, $\eta_p^2 = .38$, with fewer distractor fixations in the last bin of trials. The main effect of distractor was also significant, $F(3, 57) = 107.0$, $p < .001$, $\eta_p^2 = .47$, but importantly, the distractor effect did not change over time, as reflected in a nonsignificant interaction between the variables, $F < 1$.

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[2] An analogous time-course analysis could not be conducted for the target fixation latencies, as the target was often not selected within a given Distractor × Target condition, resulting in many missing values (e.g., 25% of data missing in bin 1 of the aqua target condition).

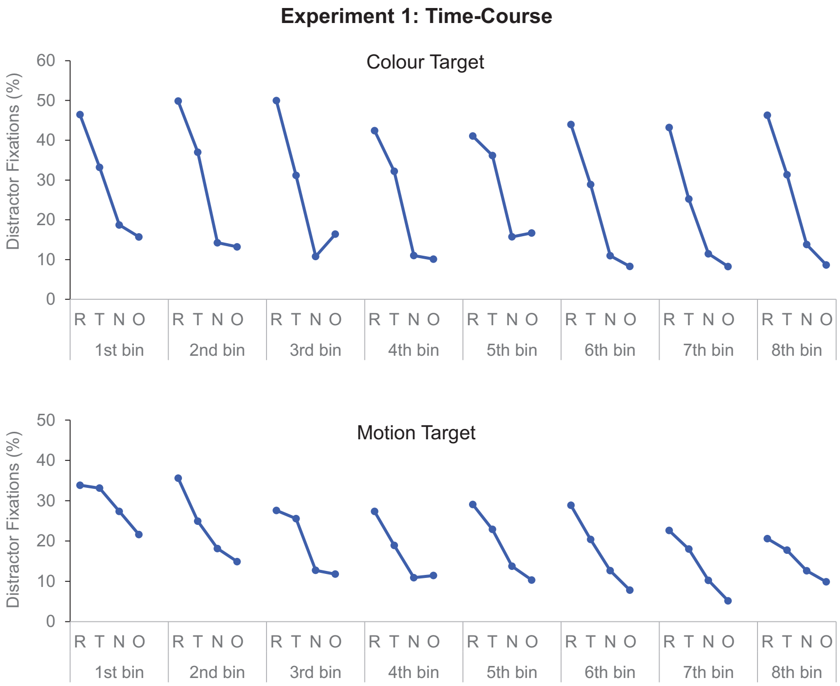


Figure 3. The proportion of distractor fixations, depicted separately for the separate trial bins of Experiment 1, the two target conditions (top: color target; bottom: motion target), and the different distractors (R = relatively matching distractor; T = target-similar distractor; N = nontarget-similar distractor; O = opposite distractor). The results show equally high or higher selection rates for the relatively matching distractor across all bins, reflecting relational search from start to finish. See the online article for the color version of this figure.

The results were also the same when we computed distractor effects across all bins with a 4 (distractor) × 8 (bins: 1–8) ANOVA. In the color target condition, the analysis showed only a significant main effect of distractor, $F(3, 57) = 45.1$, $p < .001$, $\eta_p^2 = .70$, but no significant main effect of bin $F(7, 133) = 1.7$, $p = .15$, and no interaction, $F < 1$. The motion target condition showed a significant main effect of distractor, $F(3, 57) = 29.5$, $p < .001$, $\eta_p^2 = .61$, and of bin, $F(7, 133) = 5.4$, $p = .003$, $\eta_p^2 = .22$; but no significant interaction, $F < 1$.

In summary, the data do not provide any support for the view that participants adopted a different search strategy at the beginning or toward the end of the experiment (e.g., feature-specific or singleton search). Instead, these results establish that participants adopted relational search from the start of the experiment and maintained it throughout.

Discussion

The results of Experiment 1 are in line with a relational account of dual target search: Specifically, the finding of stronger capture by relatively matching distractors than target-matching distractors is consistent with the relational account, but not the feature similarity view, which would have predicted the highest selection rates for the target-similar distractors. Similarly, there was no evidence that observers engaged in singleton detection mode. As the conditions allowed locating the targets equally well by tuning attention to the relative features of the targets or their exact feature values, the results indicate that relational search is preferred to feature-specific search and singleton detection mode.

Automatic priming effects cannot account for the results pattern of Experiment 1, as priming had only weak to moderate effects on capture, and higher selection rates by the relatively matching distractor than the target-similar distractor was observed also on switch trials, when the target was not repeated. This rules out that capture by the distractors was driven by automatic carry-over effects, and instead suggest that attention was top-down tuned to the relative color and motion characteristics of the two possible targets.

The data do not allow a clear conclusion about whether attention was tuned in parallel to the two different targets, or whether observers switched between color and motion across trials. However, there were only small switch costs when the target dimension changed across trials, and repetition effects were especially weak and unsystematic for the motion target, suggesting that attention was tuned in parallel to the relative target features across both dimensions.

Experiment 2: Search for Targets Within a Single Feature Dimension

Experiment 1 shows that the attention can be efficiently top-down tuned to two relative target features in the dimensions of motion and color. However, it has not yet been determined if attention can also be tuned to two different feature relationships *within a single dimension*.

There are inherent limitations to relational search that render it questionable that search will be relational for within-dimension multiple-target search, as attention cannot be tuned, for instance, to two opposite relationships at the same time (e.g., larger and smaller; brighter and darker; Becker, 2010a, 2013a, 2013b). This is also known as the *linear separability effect*, which was initially attributed to bottom-up limitations in processing (D'Zmura, 1991), but was later shown to largely reflect limitations in top-down tuning (e.g., Hodsoll & Humphreys, 2001), and in particular, the requirement to tune attention to two contradictory relative features (e.g., Becker, 2010a; Brand, Oriet, Johnson, & Wolfe, 2014).

To allow a realistic test of the relational account in dual target search, we used target colors that differed in two different directions from the nontargets, but were visually very different and belonged to different color categories. Specifically, the target could either be aqua and presented among turquoise nontargets (as in Experiment 1), or it could be orange, and presented among gold nontargets (redder target condition). Tuning attention to the reddest and/or bluest items does not require tuning attention to contradictory relative features. However, the colors are also not directly aligned in color feature space (see Figure 4). Hence, the colors allow a critical test of the question whether attention can be tuned to two relative colors that differ substantially from the respective nontarget colors.

Previous research indicated that tuning attention to different features within a single feature dimension produces conflict, possibly by causing interference (e.g., Treisman & Sato, 1990), which can lead observers to adopt a singleton search mode, in which all salient items attract attention (e.g., Bacon & Egeth, 1994; or all salient items within the target feature dimension; Folk & Anderson, 2010; Harris et al., 2015). Moreover, the most prominent theories of visual search propose that attention can only be tuned to a single feature within a dimension (e.g., Guided Search 2.0; Wolfe, 1994; Wolfe et al., 1990; see also Boolean Map Theory, Huang & Pashler, 2007), which would require switching between different top-down settings when attention is initially tuned to the wrong target feature (i.e., to the target that is not present in a given trial). Because attention is usually tuned to the target feature that was selected on the previous trial (under conditions of target uncertainty), major theories of attention would predict large differences between repeat trials and switch trials when the target features vary within a dimension. Thus, switch trials should either show a decrement in selectivity, with search becoming more vulnerable to distraction by all salient distractors, or show a general decrement in performance, such as elongated target fixation latencies, which would reflect the time needed to change top-down tuning to the current target feature.

According to the relational account, large switch costs (e.g., of the magnitude of 50–100 ms) should only occur when the relative feature of the target reverses (e.g., from bluer to not-bluer or from smaller to larger), as is the case when the target and nontarget features directly switch (e.g., Becker, 2010a, 2013a; Becker, Valuch, & Ansorge, 2014; see also Kristjánsson et al., 2002). If the target feature changes such that it has the same relative feature as

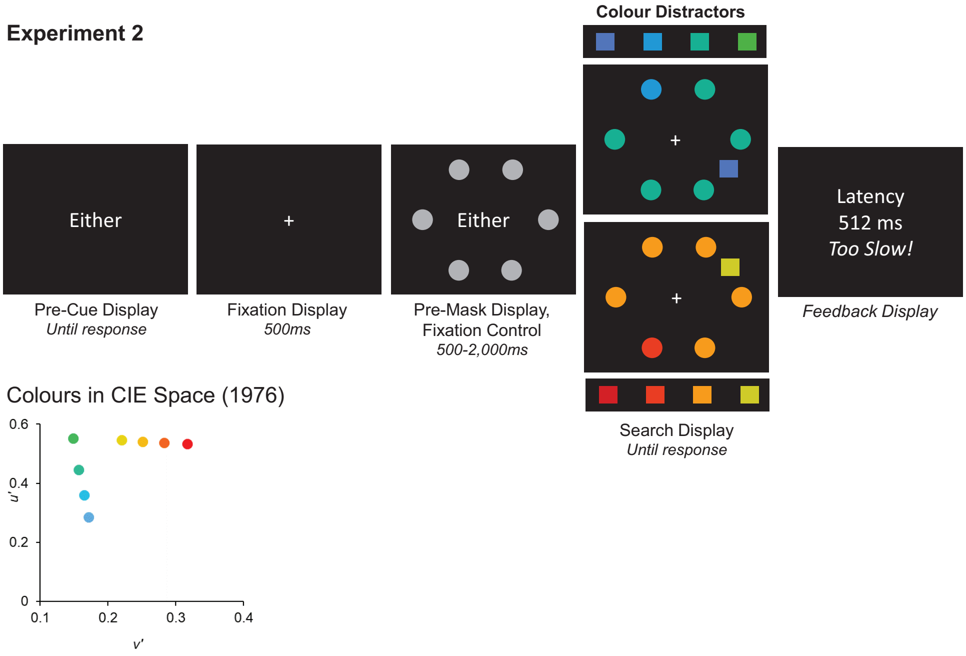


Figure 4. The top panel shows the sequence of displays in Experiment 2, where participants had to search for an aqua (greenish-blue) target among turquoise (greenish) nontargets (top), or for an orange target among yellow-orange nontargets (bottom). The color of upcoming target was either validly precued (50% trials) by the words "Aqua" or "Orange" (50% of trials), or preceded by a noninformative cue ("Either"), to indicate that either target was possible. The bottom panel shows the position of colors in CIE (1976) color space. See the online article for the color version of this figure.

the nontargets, only minimal or no switch costs should occur. However, previous studies only tested target and nontarget feature changes when the feature relationships either directly repeated or reversed, so that it is currently unknown whether switch costs would also occur when the target's relative features differ substantially from the previous target. Similarly, it is currently unknown whether it is possible to conduct multiple-target search by tuning attention to two relative features within a single stimulus dimension.

As several theories predict that multiple-target search cannot be conducted within a single feature dimension (e.g., Wolfe, 1994), at least not without first switching to the current target feature, we added a *precue* condition to Experiment 2. In one blocked condition, a word precue always validly indicated the target color on the subsequent trial (aqua or orange). In another block of trials, the precue only indicated that either target was possible (neutral precue).

If attention cannot be effectively tuned to two possible target features (or relative features) within the color dimension, we would still be able to critically test whether attention is tuned to the specific target feature value or the relative target feature because we included the valid precue condition, which allowed tuning attention in a top-down controlled manner to the upcoming target (e.g., Becker, Lewis, & Axtens, 2017; Müller, Reimann, & Krummenacher, 2003). An inability to tune attention to two colors would be reflected in large differences between the neutral and valid precue conditions, with the neutral condition showing only poor or no selectivity. By contrast, if tuning attention to two differently colored targets presents no particular challenges for the visual system, we would expect very similar results across the two precue conditions.

The manner in which attention was tuned to the target was assessed in the same way as in Experiment 1, by inserting irrelevant distractors and monitoring the eye movements of the observers. The distractors in the aqua/bluer target condition were the same as in Experiment 1 (blue, aqua, turquoise, and green). In the orange/redder target condition, the onset distractors could be red (relatively matching), orange (target-similar), gold (nontarget-similar), or yellow (opposite). If attention is tuned to the exact feature values of these targets, the target-similar, aqua and orange, distractors should attract attention and gaze most strongly. However, if attention is tuned to the relative features of the targets, the relatively matching blue and red distractors should attract attention most strongly, as these distractors matched the relative features of the target best (as they were the reddest/bluest items in the display). Finally, if observers engage in a singleton search mode (Bacon & Egeth, 1994), all salient distractors should attract attention and the gaze, reflecting the absence of selectivity within the color dimension.

Method

Participants. The sample size of the present experiment was based on the observed effects in Experiment 1 (bluer target condition), where the relationally matching (blue) distractor was selected more frequently than the target-similar (aqua) distractor. The G*Power software computed that detecting a corresponding effect ($\eta_p^2 = .483$; $M_{\text{diff}} = 12.1\%$, $SD = 13.2$, $dz = 0.924$) with a power of .90 would require 12 participants (15 participants to achieve a power of 0.95). In Experiment 2, we tested 16 participants (5 men, $M_{\text{age}} = 20.4$) with normal or corrected-to-normal vision. Participation was voluntary and participants were compensated with $10AU/hr.

Apparatus. This was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: The premask display and the target and nontarget stimuli were all disks (diameter: 1.66°), whereas the distractor was always a square (size: 1.48° × 1.48°; for a similar design, see Becker, Harris, et al., 2014, Becker, Lewis, & Axtens, 2017). A word cue (Arial Black, 12pt) was added to the center of the premask display, which could either inform observers of the identity of the upcoming target ("Aqua" or "Orange"), or provided no information about the upcoming target display ("Either"). The motion target was replaced with a color target that was orange and presented among gold (yellow-orange) nontargets. The four possible distractors in the redder target condition could be red, orange, gold, or yellow. The colors were matched for luminance with a CRS ColorCal MKII colorimeter, and had the following luminance and CIE (1976) color values: blue, L*u'v'*: 14.46, 0.172, 0.284; aqua, L*u'v'*: 13.34, 0.2, 0.441; turquoise, L*u'v'*: 14.84, 0.157, 0.446; green, L*u'v'*: 13.99, 0.149, 0.551; red, L*u'v'*: 22.93, 0.317, 0.532; orange, L*u'v'*: 23.67, 0.289, 0.537; gold, L*u'v'*: 24.41, 0.241, 0.541; yellow, L*u'v'*: 24.43, 0.22, 0.546 (see Figure 4).

Design. Experiment 2 included different types of precues as an additional factor in the design, resulting in a 2 (cue type; informative/'cued' vs. uninformative/'uncued') by 2 (target identity; aqua or orange) × 4 (distractor type; relatively matching, target-similar, nontarget-similar, and opposite) within-subjects design. As with Experiment 1, the trials (total 768) were mixed, such that the cues (informative, noninformative) targets (orange, aqua) and four distractors varied randomly within each block, while ensuring an equal number of each trial type.

Procedure. This was the same as in Experiment 1, with the following exceptions: First, all observers were instructed about the precues and instructed to use the valid precues to aid their search for either the orange or aqua target (and to prepare for either target when the precue did not specify the target). Second, each trial started with the precue presented centrally on a black screen. Once observers pressed the space bar to indicate that they had read the word precue, a fixation display was presented for 500 ms, followed by the premask display that again contained the word precue in the center of the display. The premask display was yoked with a fixation control, and the search display was presented once observers had fixated on the center of the screen for at least 700 ms, plus a random period between 1 and 200 ms, within a time window of 2,000 ms. As in Experiment 1, observers were instructed to make a fast and precise eye movement to the target while ignoring the distractors, and to press a mouse button while they were still fixating on the target to indicate that they had found the target.

Results

Data. Using the same exclusion criteria as in Experiment 1 led to a loss of 8.42% of all trials; 8.28% of trials because the first eye movement could not be assigned to a stimulus, and the remaining 0.14% because the first eye movement latencies were below 50 ms or above 1,000 ms.

Proportion of first distractor fixations. The majority of first eye-movements were directed to either the target or the distractor (>86% of first saccades across all condition averages when precued, >83% for all uncued conditions).

A 2 (repetition: target repeat vs. switch) × 2 (target identity: aqua/orange) × 2 (cue type; cued/uncued) × 4 (distractor: relatively matching, target-similar, nontarget-similar, opposite) within-subjects ANOVA revealed only a significant main effect of distractor type, $F(3, 45) = 36.2$, $p < .001$, $\eta_p^2 = .71$, but no other significant main effects or interactions, all *F*s < 2.2, *p*s > .12. These results reflect that distractor selection rates were similar across the two precue conditions, target conditions (orange, aqua), and on repeat and switch trials.

Probing the data in more detail for a possible precueing effect showed that precueing did not produce any changes in the capture rates of any of the distractors, all *t*s < 1.2, *p*s > .25, except in the bluer target condition, where valid precueing led to *more* fixations on the target-matching, aqua distractor, $t(15) = 3.1$, $p = .007$, $\eta_p^2 = .39$. Thus, valid precueing did not allow more efficient target selection or better filtering of distractors.

For better comparability with the results of Experiment 1, we have still depicted the results separately for the two targets and precue conditions (see Figure 5A and B), and limited analysis to the switch trials in the neutral precue condition, where observers had to tune attention to either target, and the data were not influenced by automatic priming effects.

In the aqua (bluer) target condition, the relatively matching, blue distractor was selected most frequently, significantly more frequently than all other distractors, including the target-similar distractor, all *t*s > 3.1, *p*s ≤ .007, $\eta_p^2 = .40–.63$. The target-similar aqua distractor also attracted a larger proportion of first eye movements than the nontarget-similar distractor and opposite distractors, but this difference was only significant compared with the nontarget-similar distractor, $t(15) = 3.1$, $p = .008$, $\eta_p^2 = .38$, not the opposite distractor, $t(15) = 1.8$, $p = .09$, $\eta_p^2 = .18$. The nontarget-similar and opposite distractor did not differ, $t(15) = 1.2$, $p = .24$.

The results for the orange (redder) target were similar: The relatively matching, red distractor was selected most frequently, significantly more frequently than the other distractors, all *t*s > 2.4, *p*s ≤ .029, $\eta_p^2 = .28–.61$. The target-similar, orange distractor was also selected more frequently than the nontarget-similar gold or opposite, yellow distractor, both *t*s > 2.4, *p*s ≤ .026, $\eta_p^2 = .29-.39$, whereas the nontarget-similar and opposite distractors did not differ, $t < 1$, $p = .53$. These results are similar to the results of Experiment 1, and indicate that attention was biased to the relative colors of the two targets (reddest/bluest), even when they varied within a dimension (color).

Target fixation latencies. To probe the data for possible covert attention shifts, the same 2 × 2 × 2 × 4 ANOVA was conducted over the mean target fixation latencies. The results showed a main effect of the precue, $F(1, 15) = 16.2$, $p = .001$, $\eta_p^2 = .52$, reflecting that saccades were elicited earlier to validly cued targets than uncued targets. There was also a significant main effect of distractor type, $F(3, 45) = 20.4$, $p < .001$, $\eta_p^2 = .58$, but no significant main effect of target color, target repetition, or any interaction; all *F*s < 1.4, *p*s > .25. As shown in Figure 5B, precueing speeded target selection by 9 ms on average (*range* = 6–15 ms), but did not differ significantly across the different distractors.

On uncued switch trials in the bluer, aqua target condition, the target fixation latencies were longest in the presence of the relatively matching, blue distractor; significantly longer than in the presence of any of the other distractors, all *t*s > 4.0, *p*s ≤ .001, $\eta_p^2 = .52–.64$. However, target latencies did not differ in the presence of any of the other distractors (target-similar aqua, nontarget-similar or opposite), all *t*s < 1.

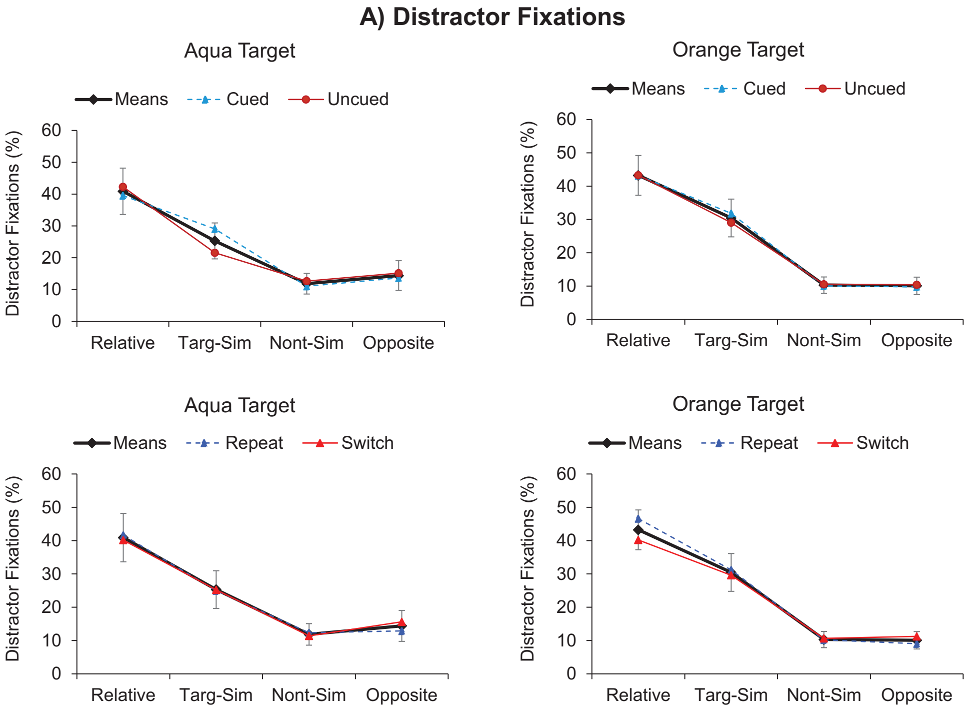
The results for the redder, orange target condition were similar, with the longest target latencies recorded in the presence of the relatively matching, red distractor, followed by the target-similar, orange distractor, and the nontarget-similar (gold) and opposite (yellow) distractors. However, none of the differences were significant with the exception of the difference between the relatively matching and nontarget-similar distractor, $t(15) = 2.2$, $p = .045$, $\eta_p^2 = .242$; all other *t*s < 1.8, *p*s > .10. With this, the results mirror the distractor fixations, as the same distractors that attracted the gaze most strongly also delayed eye movements to the targets.

Time-course of relational tuning. To assess whether relational search for the two color targets in Experiment 2 developed only later during the experiment with training, we again analyzed the distractor fixations across different trial bins (96 trials; 12 trials per distractor and target condition; pooled over repeat and switch trials, and cued/uncued trials). As shown in Figure 6, relational search was already evident within the first 12 trials in each distractor and target condition, with the relatively matching blue and red distractors attracting the gaze just as strongly or more strongly as the target-matching aqua and orange distractors.

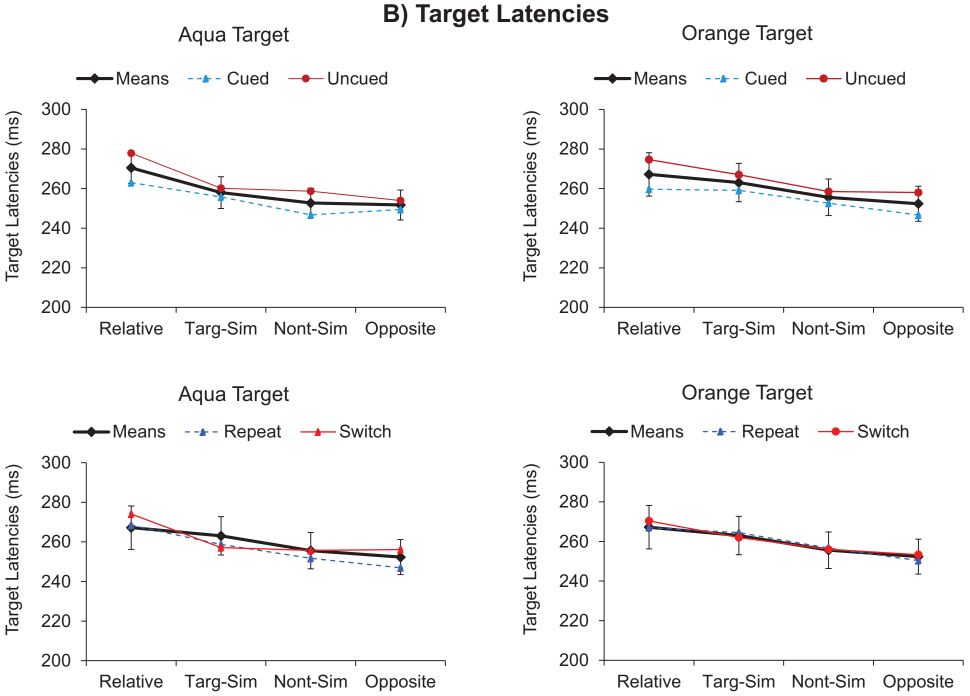
Correspondingly, a 2 × 4 ANOVA computed over the first versus last bin in the aqua (bluer) target condition revealed only a significant main effect of distractor, $F(3, 45) = 14.2$, $p < .001$, $\eta_p^2 = .49$, but no effect of bin, $F(1, 15) = 2.0$, $p = .11$, and no significant interaction, $F(3, 45) = 2.5$, $p = .096$. Comparing distractor fixations in the first versus last bin of trials in the orange (redder) target condition showed a marginally significant effect of bin, $F(1, 15) = 4.0$, $p = .064$, $\eta_p^2 = .21$, with fewer distractor fixations in the last bin (19.7%, compared with 28.2% in the first bin). There was also a main effect of distractor, $F(3, 45) = 23.1$, $p < .001$, $\eta_p^2 = .61$, but no significant interaction, $F(1, 15) = 1.0$, $p = .38$.

The results were also the same when we computed distractor effects across all bins with a 4 × 8 ANOVA. In the aqua (bluer) target condition, the analysis showed only a significant main effect of distractor, $F(3, 45) = 20.5$, $p < .001$, $\eta_p^2 = .57$, but no significant main effect of bin $F(7, 105) = 1.4$, $p = .19$, and no interaction, $F(1, 15) = 1.2$, $p = .28$. Similarly, the orange (redder) target condition only showed a significant main effect of distractor, $F(3, 45) = 33.7$, $p < .001$, $\eta_p^2 = .69$, but no significant main effect of bin $F(7, 105) = 1.7$, $p = .18$, and no interaction, $F(21, 315) = 1.2$, $p = .31$. Collectively, these results reflect that participants quickly adopted a relational search strategy in dual target search, and maintained it throughout the experiment (see Figure 6).

To assess the possibility that different participants followed different strategies, we additionally plotted the data separately for each participant (see Appendix). The results showed that only very few participants (1–3 across the different conditions) showed results consistent with singleton search or feature



A) Distractor Fixations



B) Target Latencies

Figure 5. (A) The proportion of first fixations on each of the different distractors in Experiment 2, depicted separately for the aqua target (left) and orange target (right), showed the highest selection rates for the relatively matching distractor, rather than the target-similar distractor, which supports a relational account. Performance was only weakly or not at all modulated by a valid precue specifying the target color before each trial ("Aqua," "Orange") or repeating the target across trials. (B) The mean latencies of the eye movements that directly went to the target showed similar results, with the longest delays recorded in the presence of the relatively matching distractor. Valid precueing (top panels) speeded target selection slightly, whereas repeating the target color across trials had no reliable effects. Error bars depict ±1 *SEM*. See the online article for the color version of this figure.

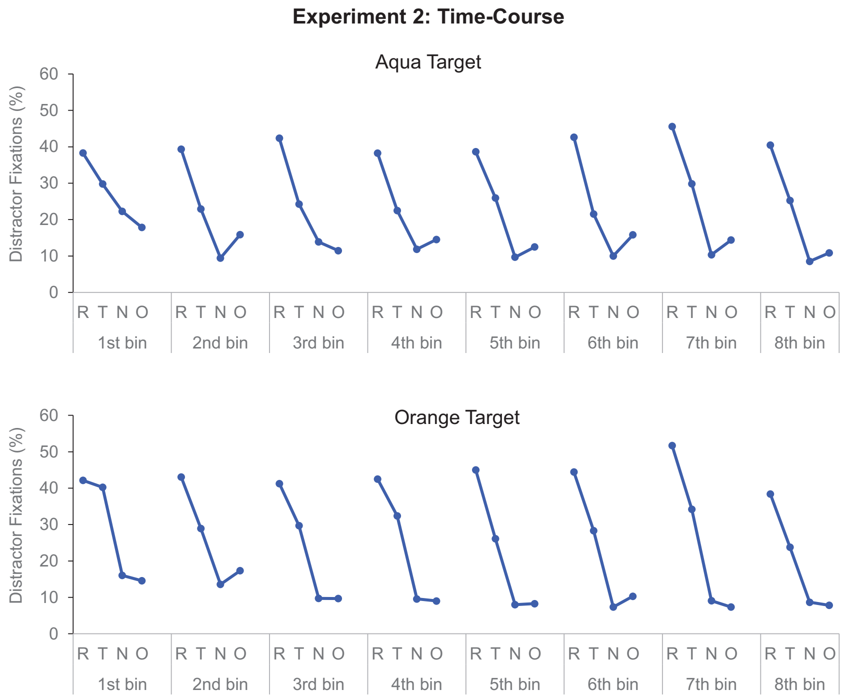


Figure 6. The proportion of distractor fixations, depicted separately for the separate trial bins in the two target conditions (top: aqua target; bottom: orange target), and the different distractors (R = relatively matching distractor; T = target-similar distractor, N = nontarget-similar distractor; O = opposite distractor). The results show that the relatively matching distractors attracted the gaze most strongly or just as strongly as the target-similar distractor, reflecting that attention was biased to the relative colors of the targets from the beginning, and throughout the experiment. See the online article for the color version of this figure.

search, whereas the majority of participants showed results more commensurate with relational search (see Appendix).

Discussion

A first important finding of Experiment 2 was that observers successfully completed the task without reverting to singleton search mode, by tuning attention to the two relevant colors of the targets. This was reflected in the large differences in capture between different distractors, which were evident both when the upcoming target feature was validly precued and when it was uncertain (on neutral precue trials). A second important finding was that attention was tuned to the relative features of the targets, rather than the exact feature values. That is, rather than tuning attention to orange and aqua, attention was tuned to redder and bluer, or toward the reddest or bluest item. Selection of the relatively matching blue or red distractors occurred even when we presented a valid word cue specifying the exact color of the target before the trial (orange, aqua). This is the first demonstration that attention can be tuned to two relative features within the same dimension, and indicates that the relational account can also accurately predict performance in dual target search.

There was little evidence for interference, or cross-talk, between the different relative features of the target (Moore & Weissman, 2010), as the effects of the precue were rather modest, and priming effects were completely absent. This indicates that the task of tuning attention to two possible relative colors was performed with relative ease, possibly by tuning attention simultaneously and in parallel to the two relative colors. If it were difficult or impossible to tune attention simultaneously to the two (relative) target colors, the results patterns in the precued and uncued conditions should have been very different, showing significantly reduced selectivity in the uncued condition. It also cannot be argued that better selectivity was achieved by deploying covert attention and identifying the (possible) target after the onset of the search display. If the target had been identified before the eye movement, we would not have observed the high rates of selecting the relatively matching distractor with the first eye movement (~40%). Similarly, it cannot be claimed that the most salient item was always selected first: Of note, the opposite distractor was also very salient, yet did not show higher selection rates than the nonsalient nontarget-similar distractor. Thus, taken together, the high degree of selectivity together with the small benefits of precueing suggest that attention was top-down tuned to the two relative colors of the possible targets.

General Discussion

In the current study we allowed observers to tune attention either to the specific features of the target or their relative features, and directly probed whether the templates were consistent with relational tuning, feature-based tuning or singleton search. Previous studies investigating single target search in similar conditions demonstrated that attention is preferably tuned to the relative feature of the target, not its exact feature value or to singletons per se (e.g., Becker, 2010a; Becker et al., 2010, 2013; Becker, Harris, et al., 2014; Harris et al., 2013; Schönhammer et al., 2016). The present study extends on these findings by showing that relational search is preferred also in dual target search; both when the two targets differ across different stimulus dimensions (motion, color; Experiment 1) and when they have different features within the same dimension (color; Experiment 2).

Of note, the targets and nontargets in the present experiments always had a constant feature value, and hence, it would have been equally possible to tune attention to the target's relative features or their absolute feature values. The finding that attention was tuned to the target's relative features shows that relational search is the preferred or *default search mode*, also in dual target search.

In particular, we failed to find any evidence that participants engage in singleton search mode. In this case, all the distractors should have attracted the gaze similarly (e.g., Bacon & Egeth, 1994; Folk & Anderson, 2010; Harris et al., 2015), contrary to our findings. Previous studies have occasionally reported evidence for singleton search mode (e.g., Bacon & Egeth, 1994), or a dimension-specific top-down tuning, in which attention is tuned to all salient items within the target dimension (e.g., color), but not to stimuli in other dimensions (e.g., motion; Harris et al., 2015). These results were interpreted in support of the *dimension weighting account* (Found & Müller, 1996; Müller, Heller, & Ziegler, 1995), originally proposed to explain intertrial switch costs when the target dimension changes from one trial to the next. However, across-dimension switch costs were obtained in a present/absent search task, in which responses are directly linked to the visual input, and later studies showed that these switch costs are mainly caused by interference in response-related processes, not early attentional processes (e.g., Becker, 2010b; Becker, Grubert, & Dux, 2014; Cohen & Magen, 1999; Kumada, 1999; Mortier, Theeuwes, & Starreveld, 2005). Eye movements typically reflect early attentional processes and are relatively insensitive to later decisional and response-related processes that operate on the stimulus-to-response mappings (e.g., Becker, 2008; Deubel & Schneider, 1996). As we used eye movements to track attention, we correspondingly failed to find any evidence for across-dimension switch costs (e.g., Becker, 2010b; Becker, Grubert, & Dux, 2014).

The failure to find evidence for singleton search mode or dimensional top-down tuning is also in line with previous studies showing a preference for a narrower, feature-based attentional bias, which is commonly found in visual search when the target is always present and needs to be focused (either for a fine-grained discrimination task, or as part of the instructions; e.g., Becker, 2008). For instance, Becker, Lewis, and Axtens (2017; Experiment 2) presented a red or green target and used a word precue before each trial to inform participants of the upcoming target color, while measuring eye movements to an onset distractor that could be red, green or blue (precued vs. uncued / unrelated). They found that even the earliest eye movements (starting 120 ms poststimulus onset) were already much more likely to select the precued distractor with the target color rather than a distractor with the uncued target color or unrelated color. These results show that top-down tuning to the target color (e.g., red or redder) reliably modulates the first eye movements, including at a very early stage of visual processing (120 ms after stimulus onset). This study could not distinguish between a feature-specific or relational search mode, but clearly showed that visual selection operates on the features of the targets rather than the entire stimulus dimension (color) or the saliency of the search items (or their feature contrast; e.g., Theeuwes, 1991).

Collectively, the studies suggest that singleton search mode or dimension-specific singleton search modes may not be a preferred or commonly observed search strategy, but may require very specific preconditions (e.g., multiple targets that are always singletons; without any competition by distractors, tight coupling of visual input with response; etc., e.g., Becker et al., 2019). More commonly, attention will be tuned to the target(s) in a narrower, feature-based manner. The present study showed that relational search is preferred to singleton search and top-down tuning to the specific feature values also in dual target search—at least when the targets and nontargets remain largely constant, and the targets can be reliably (≥50%) discriminated from the nontargets by their relative features (i.e., target is the reddest/bluest, darkest, or largest item). On the basis of previous results with a single target, it is reasonable to assume that attention would be tuned to the specific target feature(s) when relational search is not feasible (i.e., when the target is not the largest/reddest/darkest item in the display on ~50% of trials or more; Becker et al., 2013; Becker, Harris, et al., 2014; Harris et al., 2013; Schönhammer et al., 2016), but this would still need to be established by future research.

Thus, the present study extends on previous results by showing that dual target search is also relational, and that visual selection cannot be accurately predicted by assuming that attention is tuned to the specific target feature value or all salient items (singleton search mode). Moreover, the present results also extend on previous findings by providing converging evidence that relational search is genuinely top-down, and not driven by automatic priming effects. Previous studies that used a single target could not conclusively rule out that relational effects are due to automatic priming or carry-over effects that bias attention to all relatively matching items (e.g., Becker et al., 2013; Becker, Harris, et al., 2014; York & Becker, 2020).

However, as the present study used two different targets, we could separate priming effects from top-down tuning effects, and show that relational effects are due to top-down modulations of attention, not automatic priming effects (e.g., Maljkovic & Nakayama, 1994). In the color target condition of Experiment 1, repeating the target led to more eye movements toward the relatively matching distractor, indicating that attention was automatically biased to the relative color of the last encountered target (i.e., bluest item). However, across all conditions, we only analyzed switch trials, in which attention would be primed to select the wrong target (e.g., motion target rather than color target in Experiment 1), ensuring that the data would reflect top-down tuning, not bottom-up priming. Moreover, priming effects did not modulate search for the motion target in Experiment 1, or search for the color targets in Experiment 2, indicating that priming effects were overall rather weak and inconsistent.

This is in line with previous studies showing that substantial switch costs (in the order of 50–100 ms in saccadic latencies and/or 15–20% in the proportion of first fixations on the target) are caused by a misguidance effect, where attention or the gaze is directed to one of the nontarget items before the target (Becker, 2008; Eimer, Kiss, & Cheung, 2010). This typically occurs when the relative features of target and nontargets swap and the display contains one or more candidate targets that match the previous target (Becker, 2013a; Becker, Valuch, & Ansorge, 2014). For instance, large and robust switch costs can be observed when a red target is first presented among green nontargets, and then a green target among red nontargets (Maljkovic & Nakayama, 1994), but also when an orange item is first presented among all-red nontargets, and then among all-yellow nontargets (switch from yellower to redder target; Becker, Valuch, & Ansorge, 2014). In turn, switching from a yellow target among orange nontargets to an orange target among red nontargets does not incur switch costs—presumably, because the target is consistently yellower and attention is primed to select the yellowest item (e.g., Becker, Valuch, & Ansorge, 2014). Similar results are obtained in the domains of brightness, in search for greyscale targets, size targets (Becker, 2010a), or in search for a shape target (Becker, 2013a). Thus, the classical priming of pop-out effect or feature priming effect (e.g., Maljkovic & Nakayama, 1994) is relational as well. Correspondingly, selection is usually primed to the relative feature of the target rather than its absolute feature value, probably because attention is top-down tuned to the relative feature of the target (rather than its absolute feature value), as was also shown in the present study (see also Becker et al., 2013).

The lack of a strong priming effect in the present study is probably simply due to the fact that the displays never contain a candidate target item on switch trials that could successfully mis-guide attention. For instance, in Experiment 1, when selection is primed to select motion targets, the display does not contain any moving items on switch trials, which ensures that this bias does not mis-guide attention to a nontarget item or the distractor. In Experiment 2, when selection is primed to the bluest item, this bias similarly cannot influence selection, because the next display does not contain any bluer items or another bluest item that could attract attention.

In the conditions of Experiment 1 and 2, switch costs could be caused by costs of switching between different target templates in visual working memory (i.e., mental representations of the target; Duncan & Humphreys, 1989), or capacity limitations in visual working memory (VWM), of holding more than one target template in VWM. It has, for instance, been proposed that we can only effectively tune attention to a single known feature (e.g., Boolean Map theory; Huang & Pashler, 2007), or that we can only hold one feature in an activated state in VWM to effectively guide attention to this target feature (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; see also Dombrowe et al., 2011; Menneer et al., 2007, 2009). If this was true, we would have expected switch costs on uncued trials (where attention would be biased to the last selected target feature), and no switch costs but performance benefits in the informative precue condition, where the upcoming target was certain (as the valid precue allows activating the correct item in VWM). The results of Experiment 2 were consistent with this view, as we observed relatively consistent benefits in the target saccadic latencies when the target was validly precued and some repetition facilitation for selecting the aqua target (see Figure 5B). However, these benefits were quite small and not reliable across all conditions, which indicates no severe limitations in tuning attention to two different targets. With this, the present study is more aligned with the results of previous studies showing that (covert) attention can be tuned simultaneously to two different target features (e.g., Becker, Atalla, & Folk, 2020; Grubert & Eimer, 2015, 2016; Irons et al., 2012).

Admittedly, however, the present study was not designed to allow fine-grained measurements of dual target costs, and hence may not be sensitive enough to evaluate claims about whether attention can be tuned in parallel to several different targets, or has to rapidly switch between different target templates. However, what seems clear is that the switch costs and precue benefits observed with the present paradigm do not indicate any difficulties in target selection because of target uncertainty. Observers apparently did not *need* the precue to achieve high target selection rates, and neither did they rely on the previously selected target to guide selection on a given trial. This indicates that tuning attention simultaneously to two relative features lies within the capacity limitations of VWM and the visual system as a whole, and can be accomplished with relative ease, without strong interference or conflict.

Finally, we may ask whether the present results indeed support the relational account, or could alternatively be explained by combined feature similarity—saliency models (e.g., Ludwig & Gilchrist, 2002; Martinez-Trujillo & Treue, 2004), broad, categorical top-down tuning models (e.g., Wolfe, 1994; Zelinsky, Adeli, et al., 2015), nontarget inhibition (e.g., Treisman & Sato, 1990), optimal tuning (e.g., Navalpakkam & Itti, 2007; Scolari & Serences, 2009), or ideal observer models (e.g., Najemnik & Geisler, 2008).

A brief answer to this question is that the present, visual search task does not allow ruling out all of these alternative explanations, but that the results still support the relational account, because previous studies ruled out alternative explanations (using similar paradigms), and established the present results pattern as a hallmark of genuine relational search—that is, an attentional bias for feature relationships that cannot be explained with feature-specific tuning (either broad categorical tuning or narrow or optimal tuning), feature-specific inhibition, bottom-up saliency, or a combination of these principles (e.g., by showing that relatively matching cues can attract attention even when they are identical to the nontargets; e.g., Becker et al., 2013; Becker, Harris, et al., 2014; York & Becker, 2020; see also Becker, 2010a).

In addition, some considerations would also argue against using alternative models to explain these results. First, most models would need to invoke at least two different mechanisms to explain the present results, whereas the relational account only requires a single principle or mechanism, which renders the relational account more parsimonious. Second, most models (including broad categorical models) would have to rely on differences in bottom-up feature contrasts to explain more capture by the relatively matching (more salient) distractor than the target-similar (less salient) distractor. However, several studies tested whether capture by onset distractors can be modulated by bottom-up color contrasts and found no evidence for it (e.g., Becker & Lewis, 2015; Martin & Becker, 2018; York & Becker, 2020). In the present study, we similarly failed to find any differences between (nonsalient) nontarget-similar and (salient) opposite distractors, rendering a bottom-up saliency explanation not very compelling.

Moreover, despite the fact that some more sophisticated models could theoretically (be modified to) explain a subset of relational results, they typically do not predict either singleton search or relational search. Instead, at least in the context of the present experiment, the predictions derived from these models can be approximated reasonably well by assuming narrow, feature-specific tuning to the target feature value (or a slightly shifted, more optimal or ideal value) and a similarity metric (e.g., Hwang, Higgins, & Pomplun, 2009; Martinez-Trujillo & Treue, 2004; Najemnik & Geisler, 2008; Navalpakkam & Itti, 2006, 2007; Peters, Iyer, Itti, & Koch, 2005; Scolari & Serences, 2009; Zelinsky, Adeli, et al., 2013; Zelinsky, Peng, et al., 2013).[3] This prediction is also not wrong, as corresponding narrow, feature-specific tuning is well-documented and can, for instance, be observed when relational search is rendered impossible (e.g., Becker, Harris, et al., 2014; Harris et al., 2015; Navalpakkam & Itti, 2007). However, the present results show a significant deviation from these predictions, which is instructive, because it occurs in conditions that would allow feature-specific tuning, and would convey an advantage over relational tuning (e.g., by allowing more effective filtering of the relatively matching distractors).

These findings, and previous similar findings showing that relational search is applied across a large variety of search tasks could prompt rethinking if attentional guidance is indeed best modeled by a set of separate feature maps that respond to specific feature values, or whether it should be modeled with relative features in a structured feature space (i.e., in a *relational vector account*; Becker, 2010a). At a minimum, the present study adds to the growing body of evidence showing that narrow, feature-specific tuning to the target is an exception that is observed only when the conditions do not allow relational search, also in dual target search.

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[3] For instance, the optimal tuning account predicts feature-specific tuning to a feature value that can be shifted away from the target (to maximize the signal-to-noise ratio; e.g., Navalpakkam & Itti, 2007; Scolari & Serences, 2009). However, in practice, the optimal tuning account predicts shifts in color space along the blue-green axis that are maximally 0.03 *x*/*y* units. In the present study, the blue distractor was 0.11 *x*/*y* units away from the target and, therefore, a shift would not make a difference: The target-similar distractor should still attract attention more strongly than the relatively matching distractor, because it is closer to the peak of the tuning function (0.03 vs. 0.08 *x*/*y* units; see also York & Becker, 2020).

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(*Appendix follows*)

Appendix

Individual Participant's Results for Experiments 1 and 2

Dual Target Search: Attention Tuned to Relative Features, Both Within and Across Feature Dimensions; by York, Sewell, and Becker

The results of Experiments 1 and 2 were interpreted as showing that participants engaged in relational search rather than singleton search or feature-specific search when searching for two different targets (color and motion or two different colors). However, as we only displayed the average of all participants, it could be argued that perhaps only a minority of participants in Experiments 1 and 2 showed relational search, whereas others showed singleton search or feature-specific search (Figure A1).

To address this concern, we plotted the individual results for Experiment 1 (top panels) and Experiment 2 (bottom panels) below (see Figure A1). As shown in the graphs, there are only very few participants who showed evidence for feature-specific search, with more capture for the target-similar distractor than the relatively matching distractor. Evidence for a singleton search strategy is similarly sparse, as only very few participants show high capture rates for all distractors. Instead, the majority of participants shows the typical results pattern associated with relational search, with the highest capture rates for the relatively matching distractor, followed by the target-similar distractor. Collectively, these results suggest that the majority of participants searched relationally, also in dual target search.

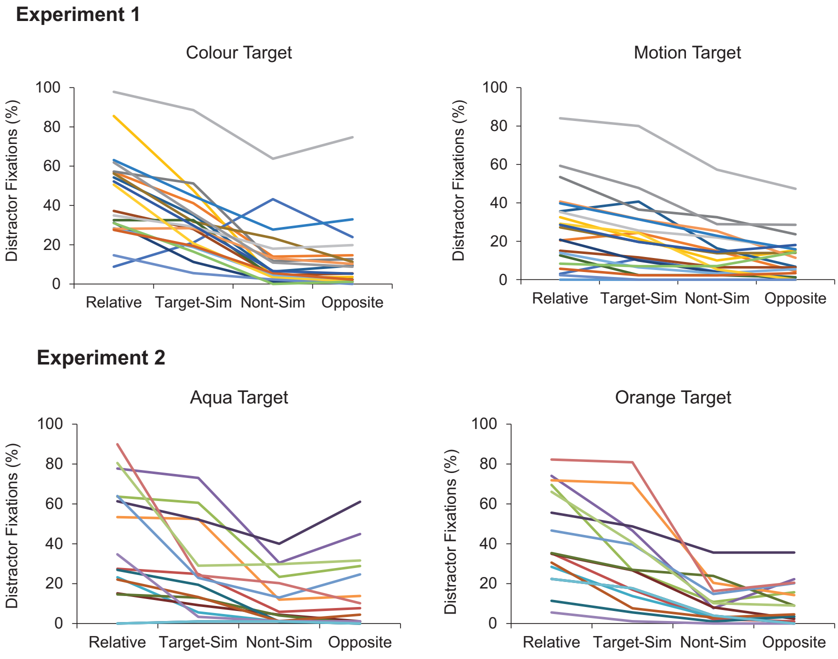

Figure A1. Fixations on the distractor in Experiment 1 (top), depicted separately for the color and motion target, and in Experiment 2 (bottom), depicted separately for the aqua and orange target. Most participants showed the typical relational results pattern, with the strongest capture for the relatively matching distractor, followed by the target-similar distractor. See the online article for the color version of this figure.

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